Probing the color structure of QCD fluids via Soft-Hard-Event-Engineering

M. Gyulassy
CCNU 10/16/17

Summary of Lecture 1:

Lattice QCD Thermodynamics Equation of State P(T), S(T)=dP/dT, E(T)=TS-P
Shows gradual “bleaching” of color electric q+g component of the QGP
As t_> Tc ~ 170 from above

Polyakov Loop L(T) and quark susceptibility $\chi_2^u = \frac{\partial^2(P/T^4)}{\partial(\mu_u/T)^2}$ Lead to different possibilities

The semi-QGP model of color electric composition near Tc depends on

Color liberation schemes

$$\chi_T = \frac{\rho_e}{\rho_{tot}} = \frac{\rho_e}{\rho_e + \rho_m} = \begin{cases} \chi_T^u = c_q \chi_2^u + c_g L^2 \\ \chi_T^L = c_q L + c_g L^2 \end{cases}$$

Fast q, Slow^2 g
Slow q, Slow^2 g

The missing “m” density is fixed by a choice of Liberation Scheme and relation of ρ to EOS

$$\rho_m(T) = (1-\chi(T))\rho_{tot}(T) = (1-\chi(T)) \begin{cases} P(T)/T \\ S(T)/4 \end{cases}$$

The2008 AA v2(pT>5 GeV) puzzle challenged perturbative dEdx models of jet dEdx.
But can be “solved” in various ways.
Is interpreted as density

Most provocative interpretation by J.Liao&E.Shuryak is to interpret ρ_m as density
of emergent color magnetic monopoles near Tc leading to “volcano scenario” for dEdx

In Lecture 2 I review recent progress with CIBJET S.Shi,J.Liao,MG to quantify the above model

Wu Qiu Shou Wang - The Game Official, one of Xin-Nian's many 10^N Ancient Wang relatives (~100 BC)

A Brief Background History Lesson

As the Chinese saying goes, 'Serving the King is like attending a tiger', the Game Official was a tough position. If you lose to the king, he will consider you a lousy player and fire you. However, if you beat the king, he is not going to be happy, because no one likes to lose. Thus Wu Qiu Shou Wang was soon fired by the king. He begged Wu Di to let him stay in the palace and take care of the royal horses, but Wu Di turned him down. He eventually asked for permission to join the army in fighting the Huns (Humgarians), and Wu Di accepted his request.

http://www.yutopian.com/chinesechess/stories/wushou.html

http://www.yutopian.com/history/xihan.html

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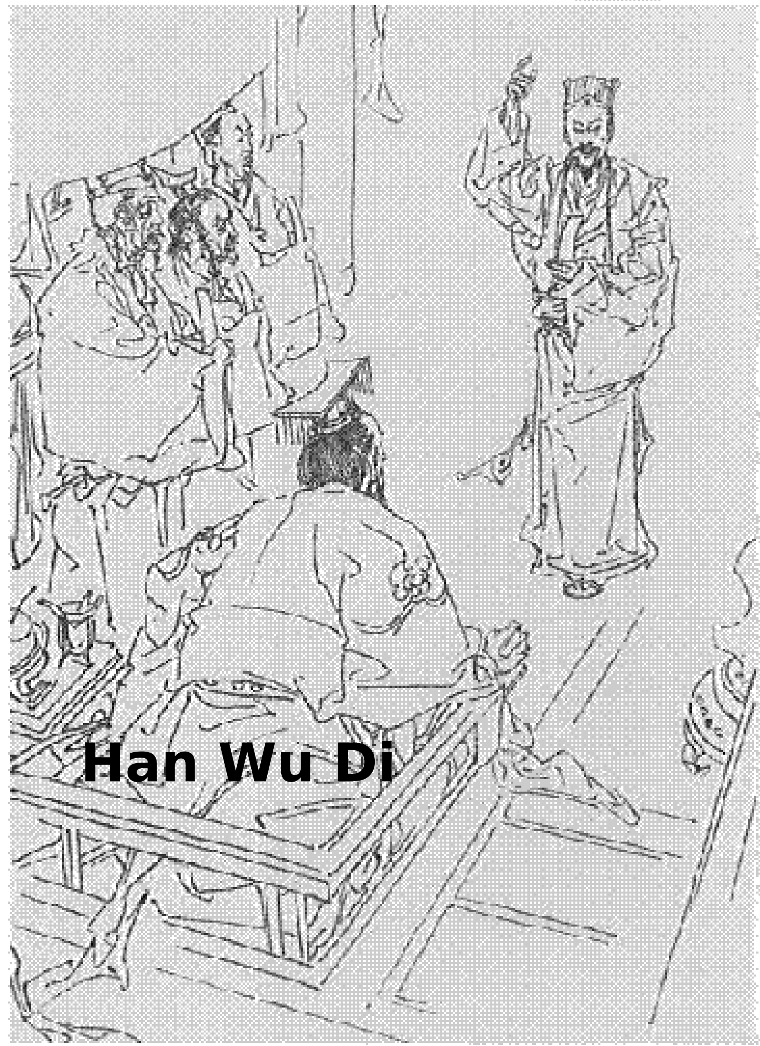

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My great luck is that XinNian's relatives did not wipe out my Hun relatives and that I could enjoy 27 years so far of fruitful and fun Han-Hun collaborations

(continuing now as a Bian Peng Visiting Professor at CCNU since 2015)

"Probing the Color Structure of "Perfect" QCD Fluids produced at RHIC and LHC

via Soft-Hard-Event-Engineering (**SHEE**)"

Miklos Gyulassy

CCNU, LBNL, Columbia U, Wigner/MTA

Non-perturbative QCD makes Perfect Fluid P(T) < $P_{SB} = \left(2_s \times 8_c + \frac{7}{8} \times 2_s \times 3_c \times 2_{q\bar{q}} \times N_f\right) \frac{\pi^2 T^4}{90}$

What are the color d.o.f. in the QCD fluid near Tc that cause $\frac{\eta}{s} \sim O(1/4\pi)$?

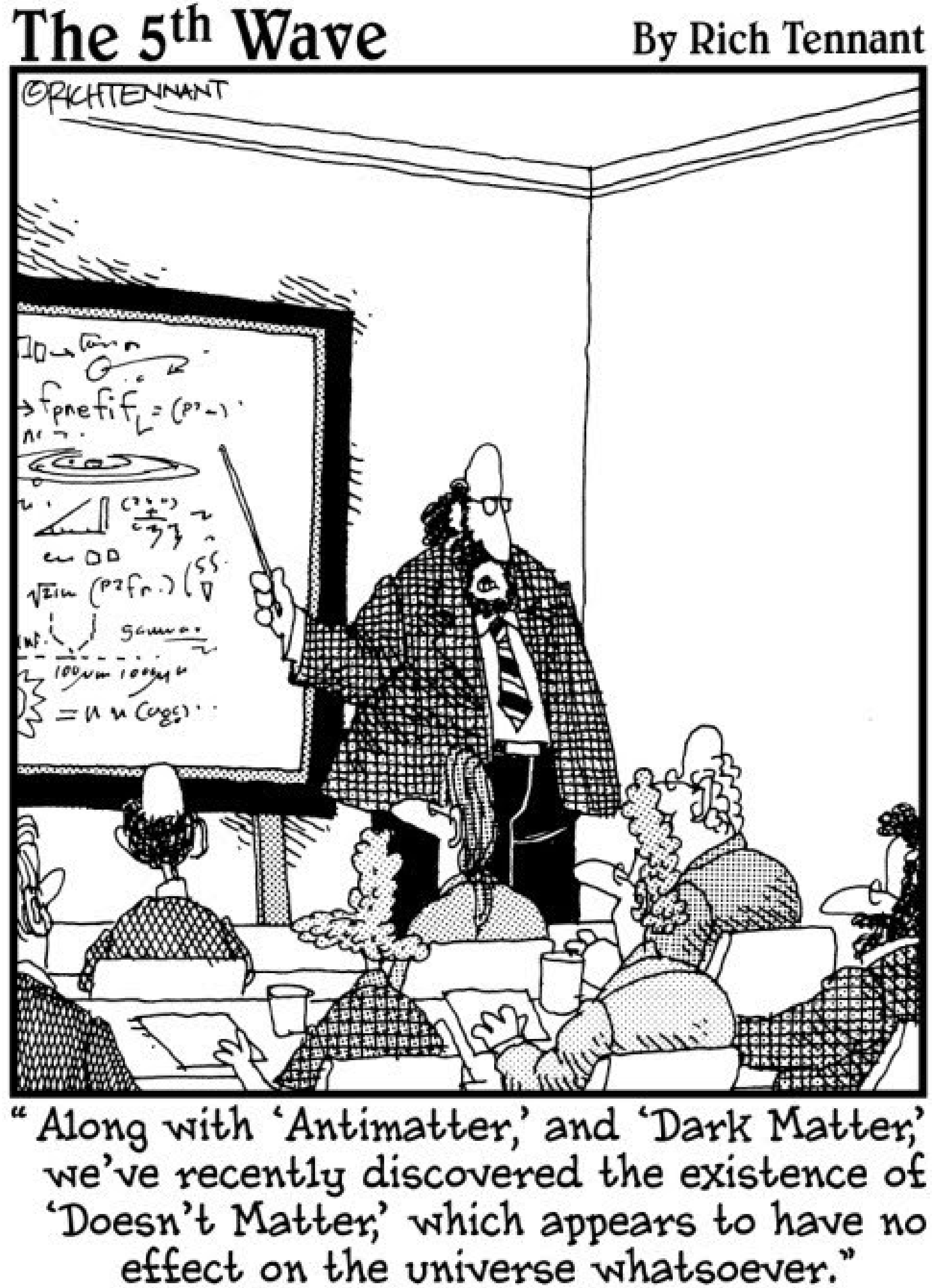
Can we exploit **correlations** between **soft** collective flow observables, $v_n(p_T<2$ GeV),
And **hard** jet quenching observables, R_{AA}, v_2, v_3 (pT>10 GeV), at RHIC&LHC to find out?

Lec 1: General intro. Start review of (**ebe-IC+vUSPH+BBMG**) hydro **SHEE** and soft+hard v_n assuming a perturbative **wQGP** color structure for quenching of jets. This provides one *sufficient* solution to old soft+hard data puzzles. (Jaki Noronha-Hostler, BB, JN, MG 2016)

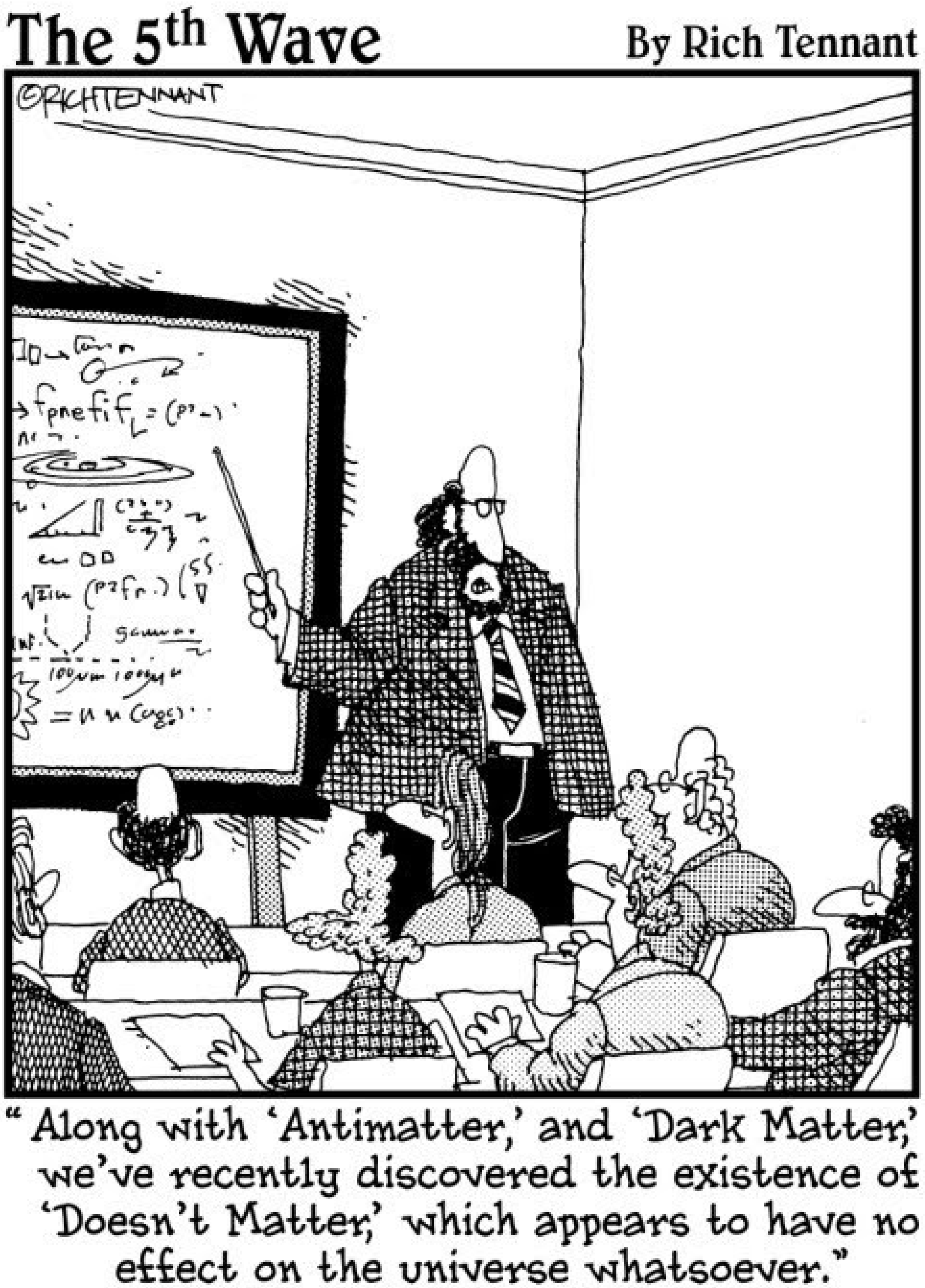
Lec 2: Update of **CIBJET** (Columbia-Indiana-Berkeley)= ebeCUJET3 extending last year's **VISHNU2+1** X **CUJET3** to study effects of event-by-event IC fluctuations on observables. CIBJET assumes a multicomponent semi-QGP+Mag.monopole (**sQGMP**) color structure of the QCD fluid. We find that this framework provides a second sufficient solution. (Shuzhe Shi, Jinfeng Liao, Jiechen Xu, MG 2017 in progress)

(Next problem is to try to break the degeneracy of current solutions using SHEE)

What ***is*** the Matter?



What ***is*** the Matter?



Fortunately wQGP and sQGMP models can make falsifiable SSEE & SHEE predictions that could be used in the future to break current data interpretation degeneracies

THE central goal of A+A exp+theo is to verify and quantify the

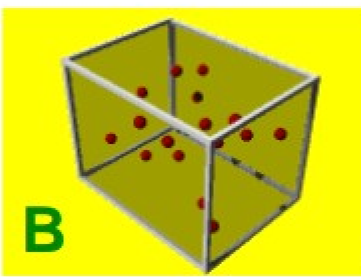
1975 QCD Prediction new form of Matter

Collins, Perry
Baym, Chin
Freedman,
McLerran,
Shuryak, …

Because QCD is Asymptotically *Free*

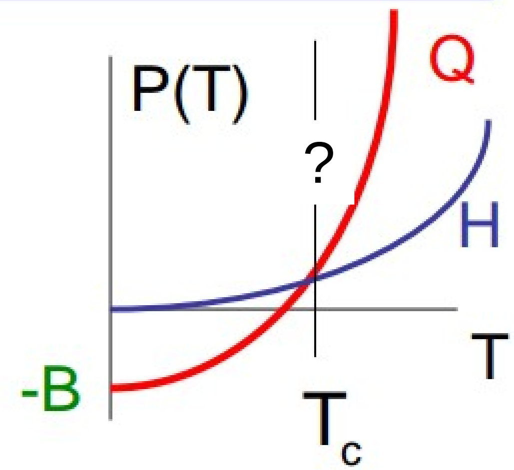
$$P_{QCD}(T) \xrightarrow{T \gg \Lambda_{QCD}} P_{SB}(T)$$

Ideal (Stefan-Boltzmann) Pressure at g→0



$$P^{QCD}_{SB}(T) = (\underbrace{2_s \times 8_c}_{\text{gluons}} + \tfrac{7}{8} \times \underbrace{2_s \times 3_c \times 2_{q\bar{q}} \times n_f}_{\text{quarks}})\frac{\pi^2 T^4}{90} - \underbrace{B}_{\text{vac}}$$

$$P^H(T) = (\underbrace{3_{iso}}_{\text{pions}} + \underbrace{O(e^{-M/T})}_{\rho,\omega,\cdots})\frac{\pi^2 T^4}{90}$$



$$T_c = \left(\frac{B}{K_Q - K_H}\right)^{1/4} \approx \Lambda_{QCD} \approx 150 - 200\,\text{MeV}$$

$T>T_c$

De-Confinement of gluon and quarks color degrees of freedom

Screened Yukawa Interactions $V_{q\bar{q}}(r) = \alpha_s(T)\dfrac{e^{-\mu(T)r}}{r} \xrightarrow[T\to\infty]{\mu=gT} 0$

Chiral $SU(2)_L X SU(2)_R$ Symmetry restored

u, d, g, “M” $\langle\bar{\psi}\psi\rangle_{T>T_c} \approx 0$

Color bleached *semi*-QGP ??

$T=T_c \sim 150\text{-}170$ MeV

sQG”M”P ??

- **Color mag.monopoles condensation ??**

π, K, p $\langle\bar{\psi}\psi\rangle_{T>T_c} \approx -\Lambda^3_{QCD}$

$T<T_c$

Confinement of g,q into Color White Composite Hadrons

Effective String Interactions: $V_{q\bar{q}}(r) = -\dfrac{\alpha}{r} + \kappa r \to \infty$

Chiral Symmetry Broken: $SU(2)_L X SU(2)_R$ -> $SU(2)_{isospin}$

A simple "Crossover Transition" Bag Model of entropy density $\sigma(T) = (\epsilon + P)/T$

$$\sigma(T) = f(T)\sigma_H(T) + (1 - f(T))\sigma_Q(T)$$

$$f(T) = \{1 + \tanh[(T - T_c)/\Delta T_c\}/2$$

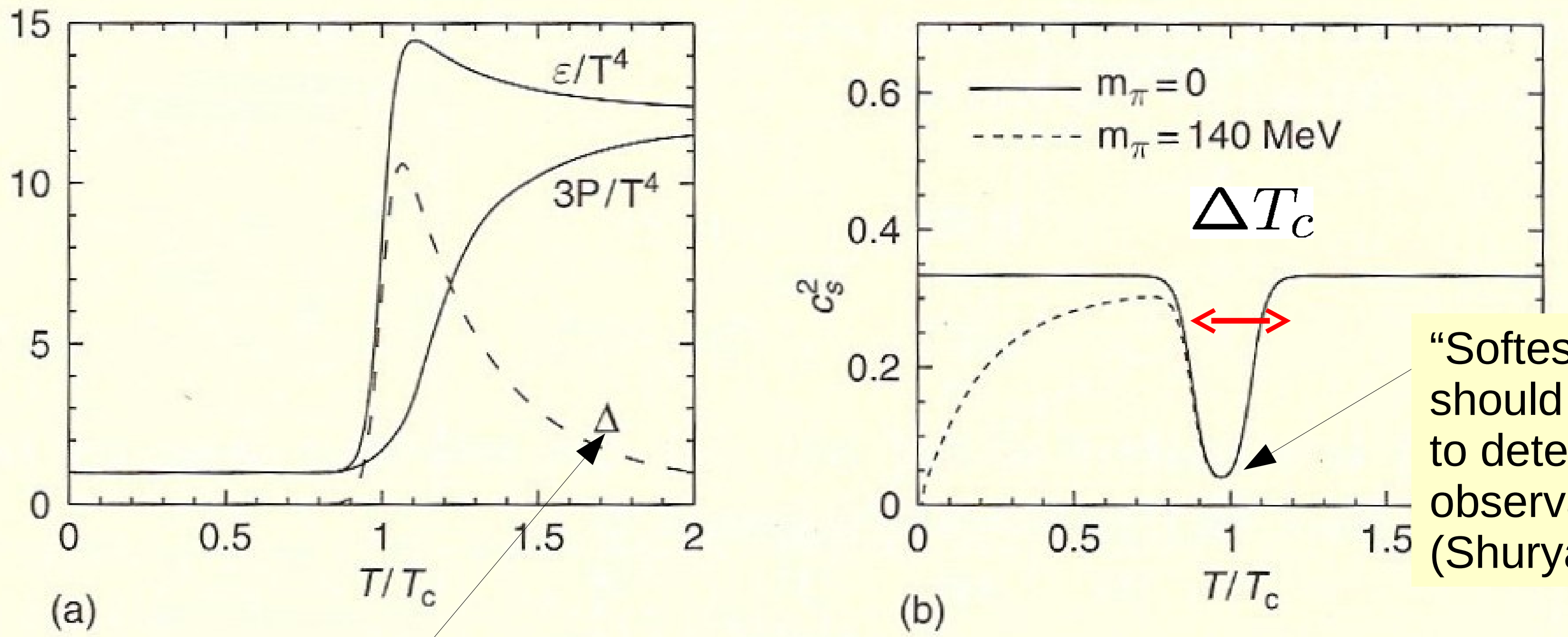


Fig. 3.4. (a) ε/T^4 and $3P/T^4$ obtained from the parametrized entropy density, Eq. (3.60), with $\Gamma/T_c = 0.05$ and $N_f = 2$; $\Delta \equiv (\varepsilon - 3P)/T^4$ is shown by the dashed line. (b) Sound velocity squared as a function of T with the same parametrization for the entropy. The figures are adapted from Asakawa and Hatsuda (1997).

"Softest Point" should be easy to detect via flow observables (Shuryak, 1995)

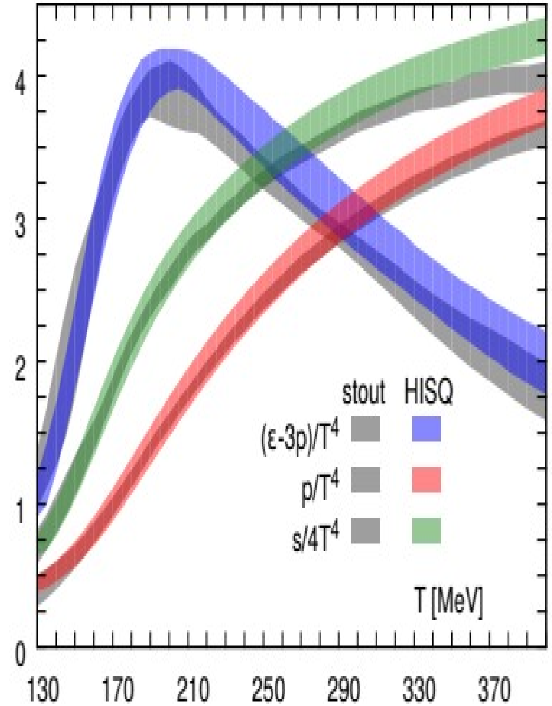
<u>QCD Conformal Anomaly</u>

Reason why *<u>conformal</u>* AdS/CFT had to be "Improved"
By extra conformal breaking dilaton and/or vector fields
(similar to nuclear matter Walecka model)

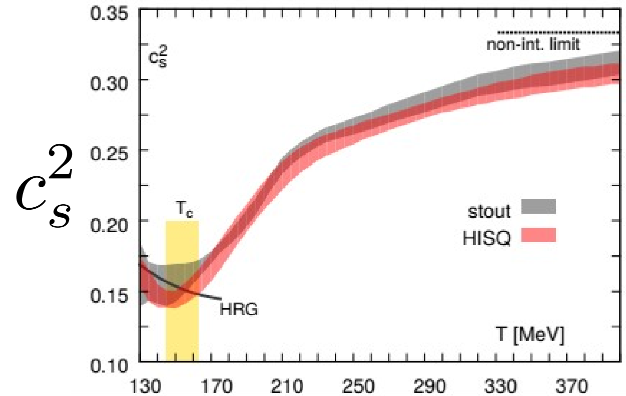
The nonperturbative medium near T_c from lattice

Thermal →

Local
Thermo-***statics***
Equation of State
Entropy density s(T)

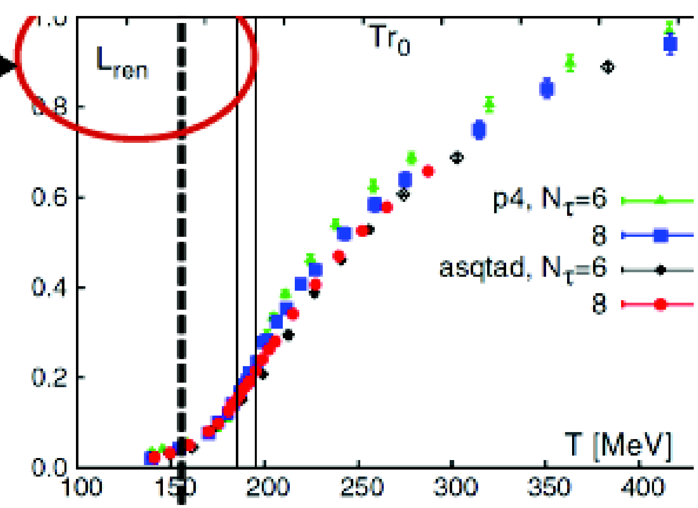


Phys.Rev. D90 (2014)
HotQCD Lattice
F.Karsh et al



Chromo →

Measure
Of free energy
Of heavy quark



arXiv:hep-lat/0405009v2
Bazavov et al PRD 2009

$$L(\mathbf{x}) = \frac{1}{N_c}\mathrm{tr}\mathcal{P}\exp\left[ig\int_0^{1/T} A_4(\tau,\mathbf{x})d\tau\right]$$

$$\langle L\rangle \propto e^{-F_Q/T}$$

$$\langle L\rangle \begin{cases} = 0, & \text{confined } (T<T_c) \\ \neq 0, & \text{deconfined } (T>T_c) \end{cases}$$

- **What would be a lattice compatible, microscopic description of the near Tc matter?**
  - Does this help reconciling the "soft" vs "hard" transport inconsistency?

The **semi-QGP** Model of deconfinement

R. D. Pisarski, PRD74, 121703 (2006)
Y. Hidaka, R. D. Pisarski, PRD78, 071501(2008)
Gale et al, PRL114,072301(2015) and refs

The simplest way to represent a phase where $\langle \ell \rangle < 1$ is to work in mean field theory, taking A_0 to be a constant, diagonal matrix, $(A_0^{cl})^{ab} = \delta^{ab} Q^a/g$ [3–6]. The Polyakov loop is then $\ell = 1/N_c \sum_a e^{iQ^a/T}$, where the color index $a = 1 \ldots N_c$. For three colors, $A_0^{cl} = (Q, -Q, 0)/g$, so $Q = 2\pi T/3$ in the confined vacuum, $\ell = 0$. Since $A_0^{cl} \sim T/g$, this is manifestly a model of non-perturbative physics.

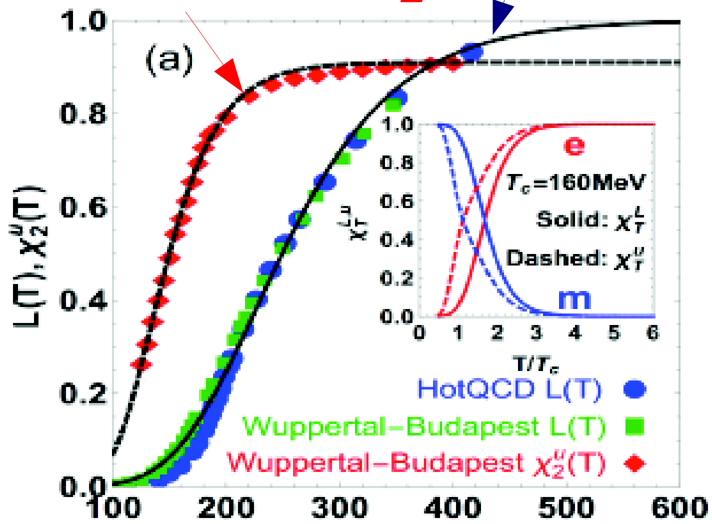
In Minkowski spacetime, the diagrams are those of ordinary perturbation theory, except that the background field A_0^{cl} acts like an imaginary chemical potential for color. For a quark with color a, the Fermi-Dirac distribution function is $1/(e^{(E-iQ^a)/T} + 1)$. In the double line basis gluons carry two color indices, (ab), and their Bose-Einstein distribution function involves a difference of Q's, $1/(e^{(E-i(Q^a-Q^b))/T} - 1)$. In the Boltzmann approximation, the distribution function for a single quark (or anti-quark), summed over color, is suppressed by the Polyakov loop, $\sim \sum_a e^{-(E-iQ^a)/T}/N_c \sim e^{-E/T}\ell$; for gluons, it is $\sim e^{-E/T}\ell^2$.

Density of color **electric** monopoles suppressed by L(T)

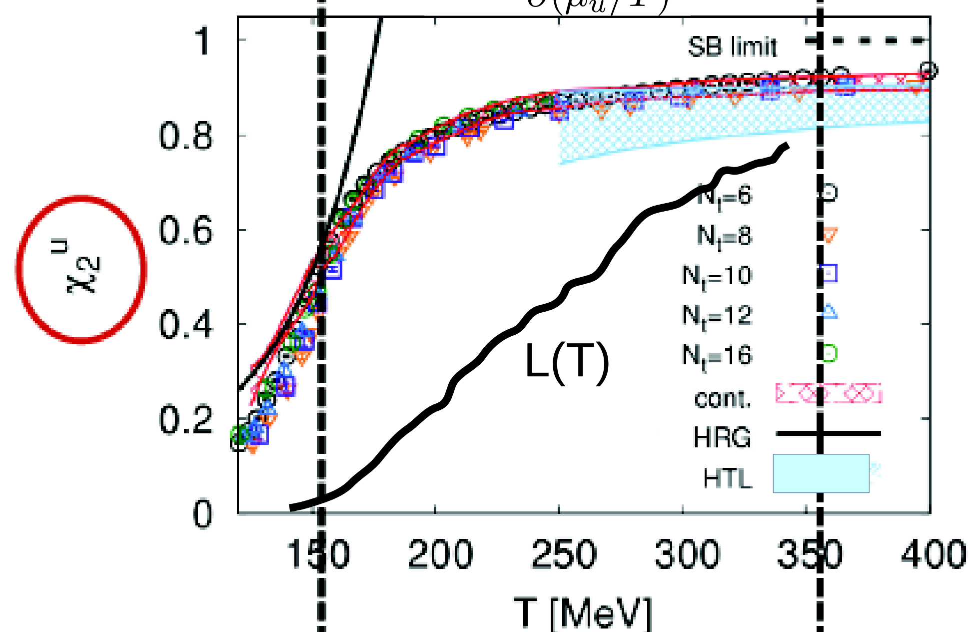
$$\rho_{q+g}(T) = L(T)\rho_g^{SB}(T) + L(T)^2\rho_g^{SB}(T)$$

<u>Alternate Model:</u> Quark number susceptibility vs Polyakov loop

"Fast Quark liberation χ_2^u" "Slow Quark liberation L(T)"



$$\chi_2^u = \frac{\partial^2(P/T^4)}{\partial(\mu_u/T)^2}$$

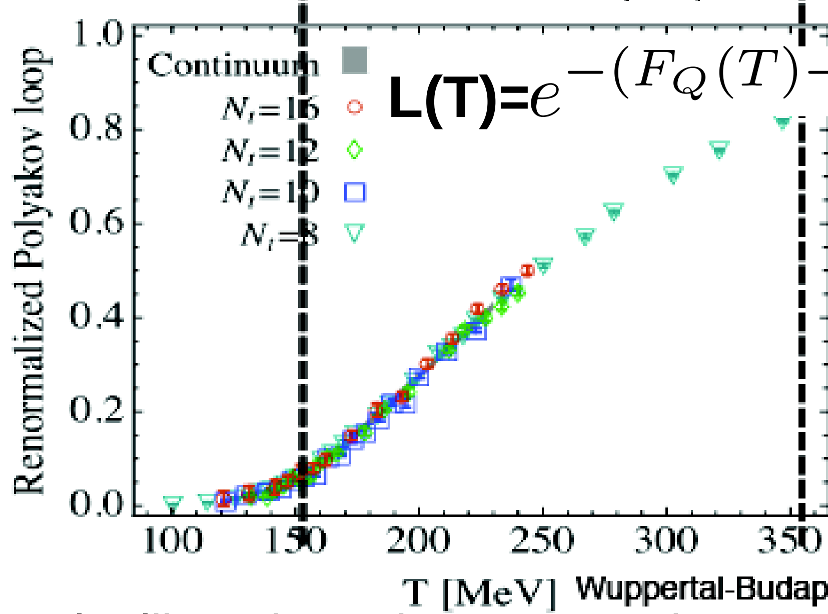


JHEP 1201, 138 (2012)

Different Models of Color "Bleaching" for T>Tc
Slow L :Hidaka,Pisarski etal,PRL114(2015)
Fast χ_2^u :P.Petreczky etal, HotQCD

CUJET3 JX, Liao, Gyulassy, arXiv:1508.00552

$$\frac{\rho_e}{\rho_{tot}} = \begin{cases} \chi_T^u = c_q\chi_2^u + c_g L^2 \\ \chi_T^L = c_q L + c_g L^2 \end{cases}$$



L(T)=$e^{-(F_Q(T)-M_Q)/T}$

Wuppertal-Budapest 2010

Which bleaching is correct? quark number susceptibility instead of Polyakov loop for the deconfinement rate of quarks near T_c ?

In CUJET3 we compare results with both color liberation schemes to estimate the theoretical systematic errors associated color composition

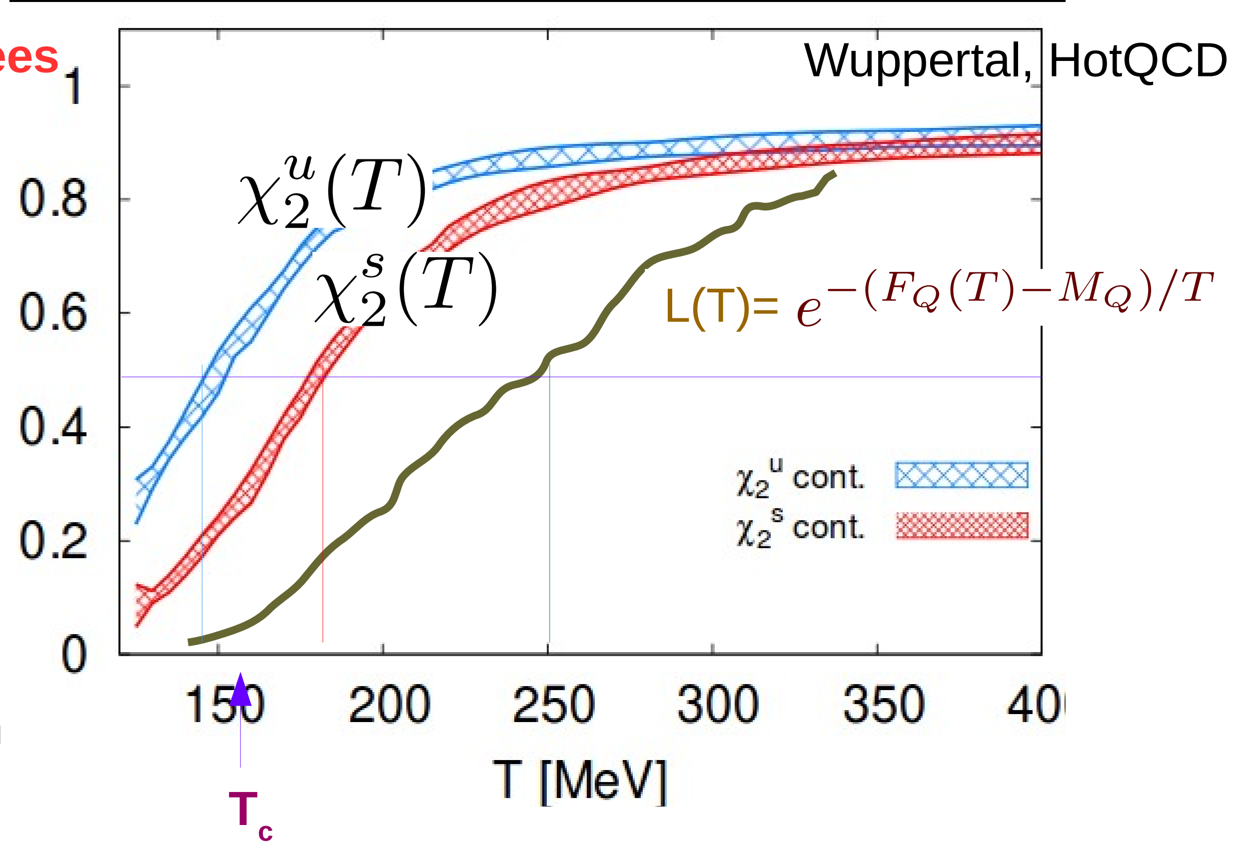
Where are the missing color degrees of freedom in a semi-QGP?

Quark color liberation from Susceptibility has mass hierarchy

$T_u \sim T_c < T_s < T_Q \sim 2T_c$

Partial pressure of quark flavor q

$$P_q(T,\mu_q) = P_q(T,0) + \frac{\chi_2^q(T)}{2}\mu_q^2 T^2 + \cdots$$



Semi-QGP is defined by suppression Of the q and g ***color electric*** dof

$$\chi_T = \frac{\rho_e}{\rho_{tot}} = \frac{\rho_e}{\rho_e+\rho_m} = \begin{cases} \chi_T^u = c_q\chi_2^u + c_g L^2 & \text{Fast q, Slow^2 g} \\ \chi_T^L = c_q L + c_g L^2 & \text{Slow q, Slow^2 g} \end{cases}$$

But $\rho_{tot} = \rho_e + \rho_m \approx S(T)/4 = (\epsilon + P)/(4T)$ is constrained by Lattice !

What are the missing “m” dof needed to account for total Lattice QCD entropy?

J.Liao E.Shuryak (2007) proposed that the missing color degrees of freedom are emergent Color Magnetic Monopoles that form below ~2Tc and then slowly condense near Tc to completely confine all color dof in the hadronic resonance/nuclear phase of QCD below Tc

In CUJET3 we tested 4 models of sQGMP composition compatible with Lattice QCD thermo

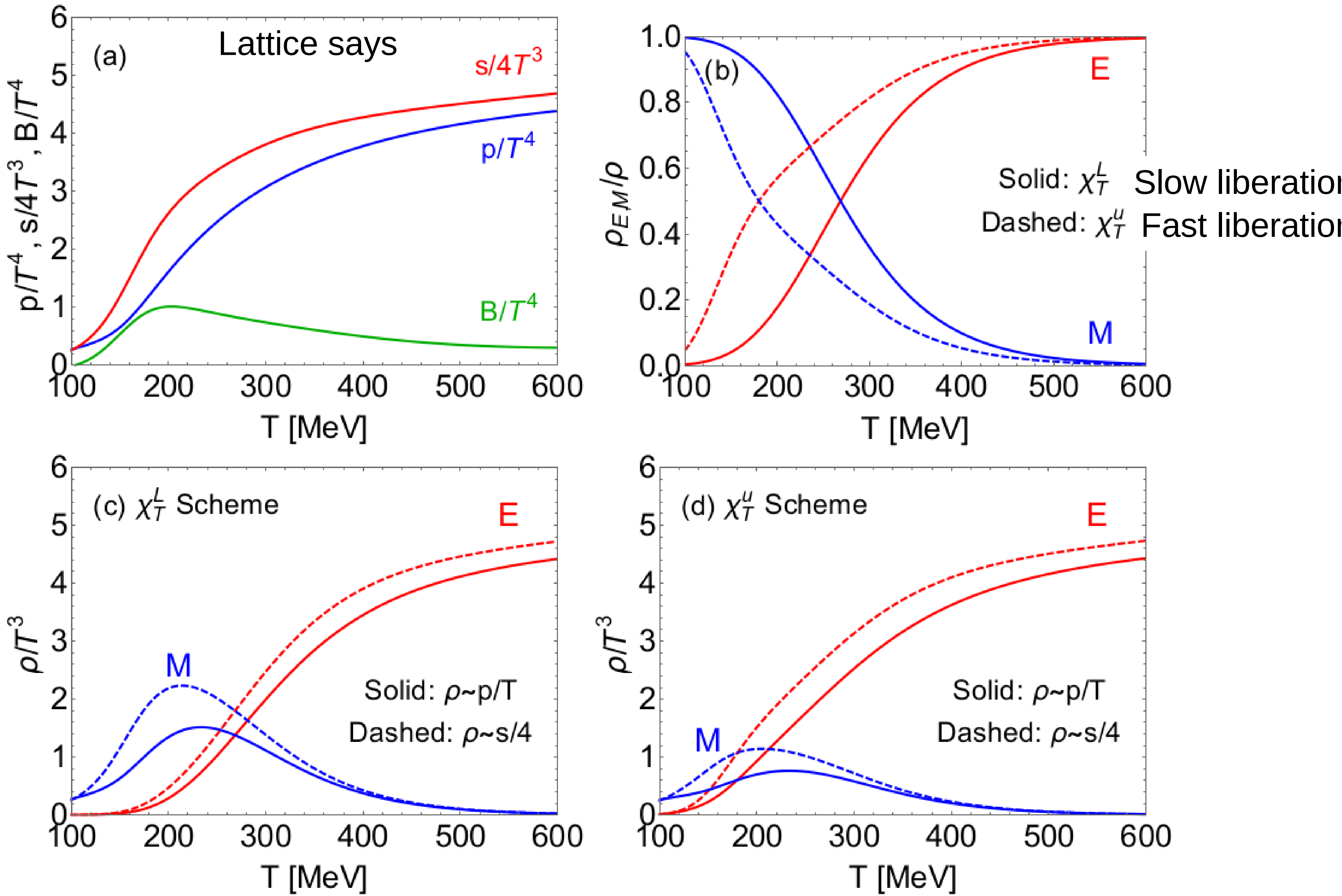
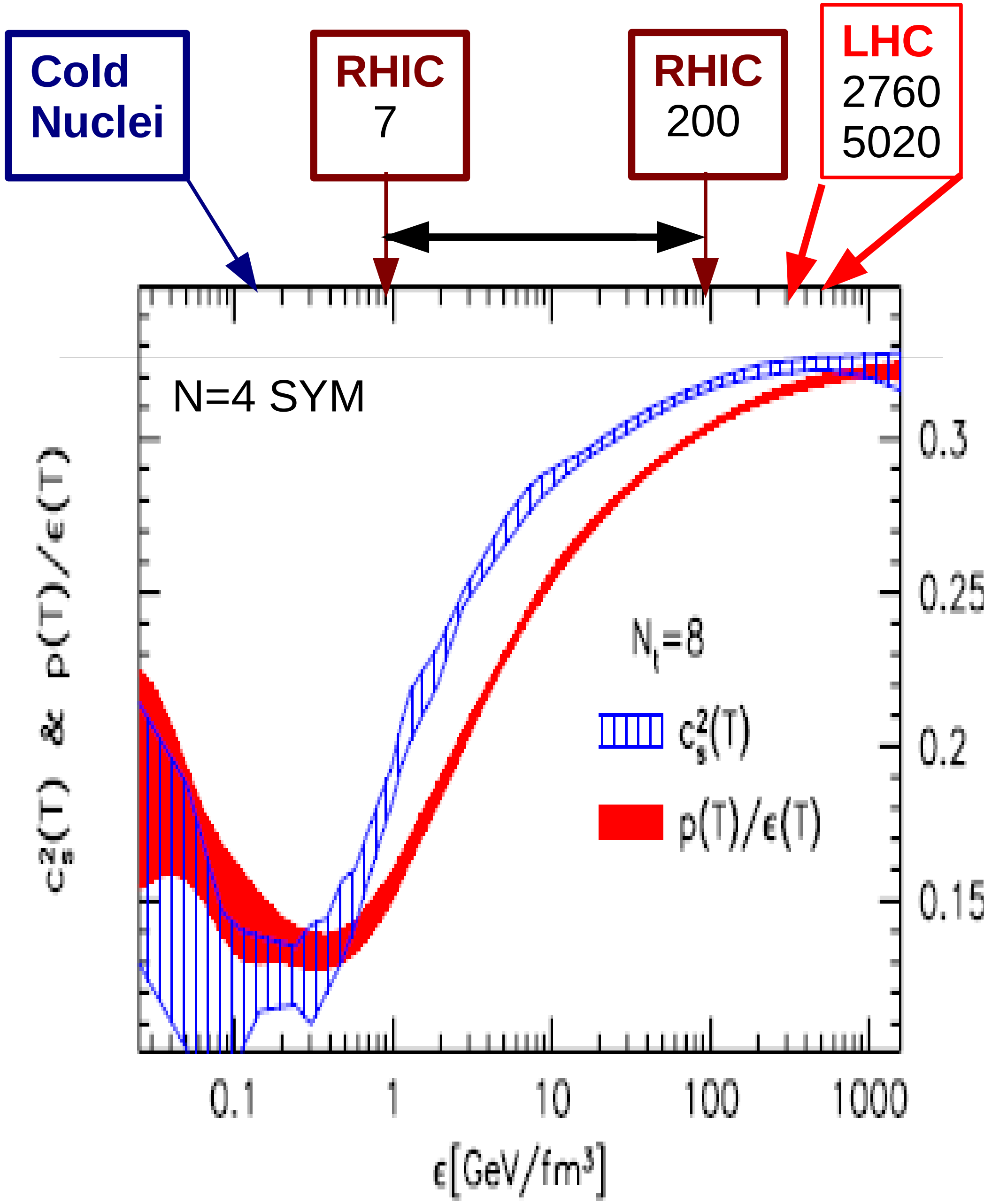


Figure 6. (Color online) (a) The effective ideal quasiparticle density, $\rho/T^3 = \xi_p P/T^4$, in the Pressure Scheme (PS, Blue) is compared with effective density, $\rho/T^3 = \xi_p S/4T^3$, in the Entropy Scheme (ES, Red) based on fits to lattice data from HotQCD Collaboration [56]. The difference is due to an interaction "bag" pressure $-B(T)/T^4$ (Green) that encodes the QCD conformal anomaly

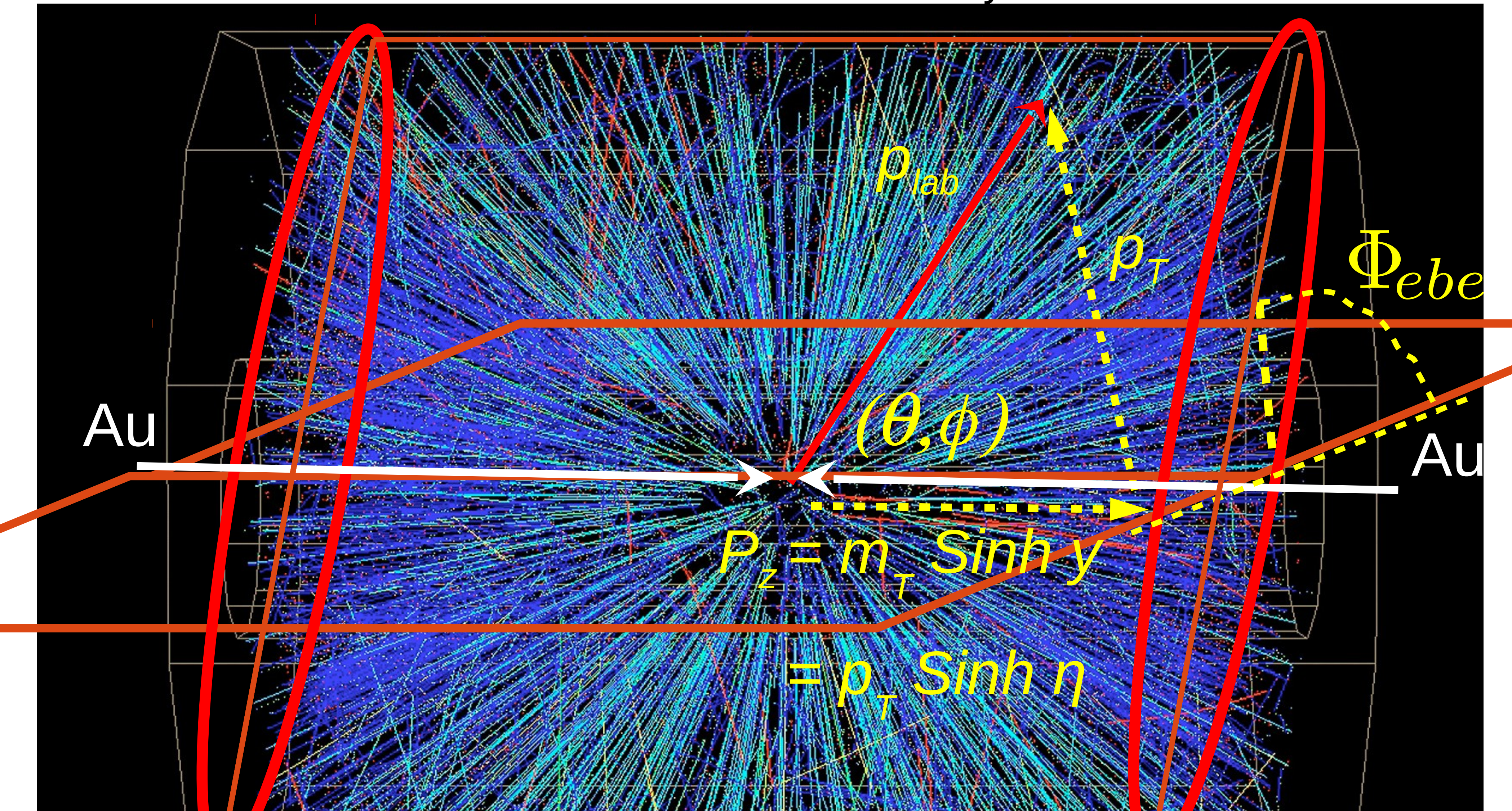
Why both RHIC and LHC A+A exp are needed map out sQGMP

Wide Beam Energy Scan capability makes RHIC essential to study Non-Conformal QCD cross-over transition T physics

Highest energy LHC essential to measure high pT> 20 GeV u,c,b Jet Quenching probes and also To test Color Glass gluon Saturation initial conditions.



Measuring (m,η, p_T,φ) of ~10^4 hadrons, photon leptons, jet quenching, and bulk collective azimuthal flow harmonics event by event

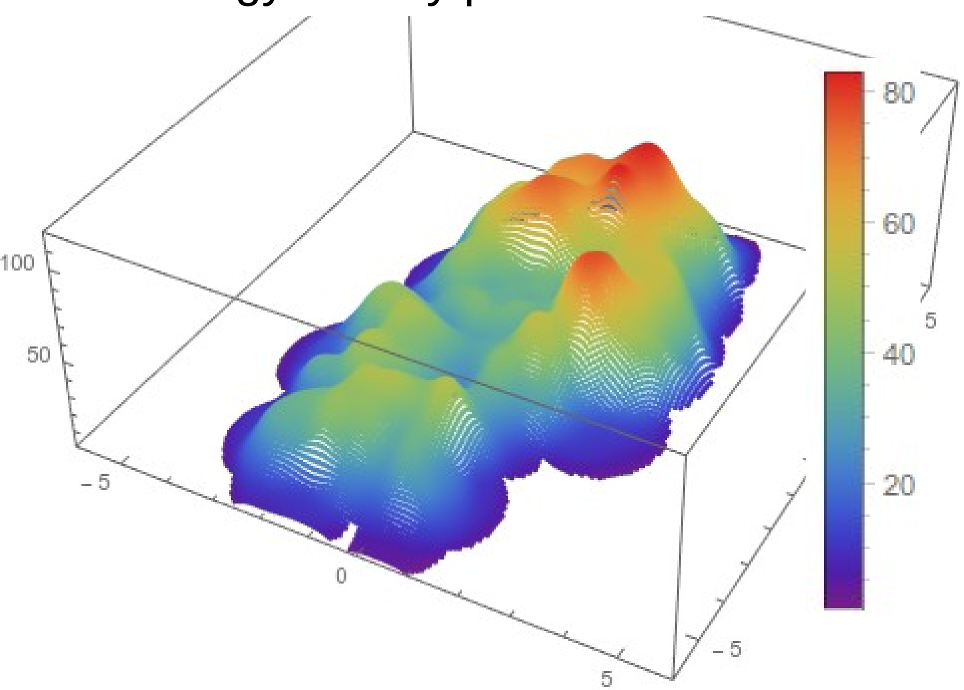


$$\frac{dN}{d\eta dp_T d\phi} = \frac{dN}{d\eta dp_T}\left(1 + 2\sum_{1}^{\infty} v_n(p_T,\eta)(n(\phi - \Phi_n)\right)$$

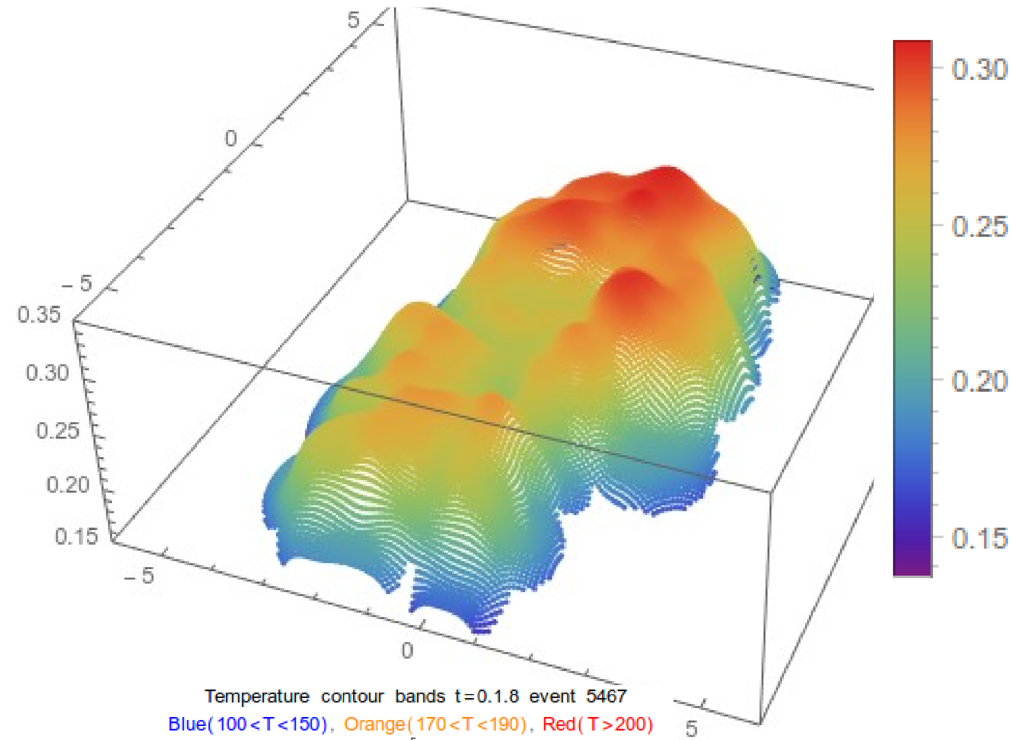
Jacquelyn Noronha-Hostler, et al PbPb2.76 20-30% inhomogeneous MCKLN vUSPH hydro

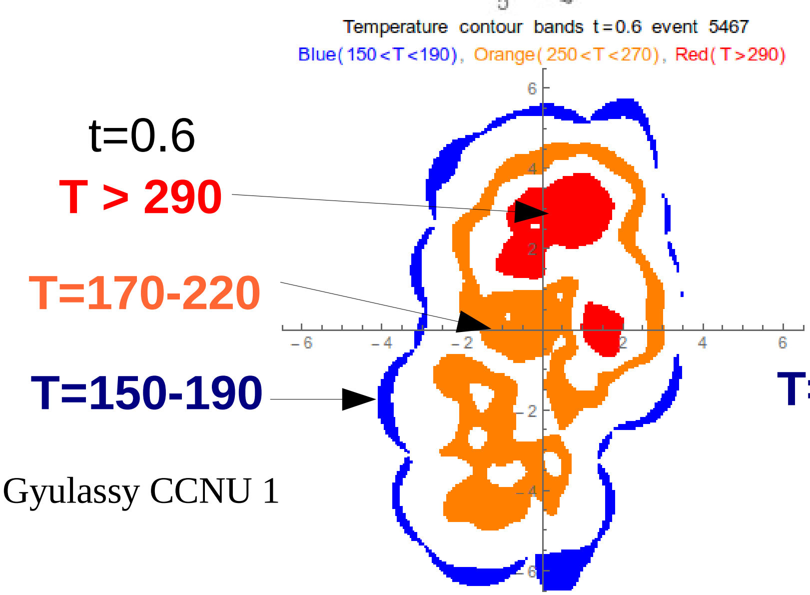
Example of a typical lumpy anisotropic evolution with **disconnected isotherm surfaces !**

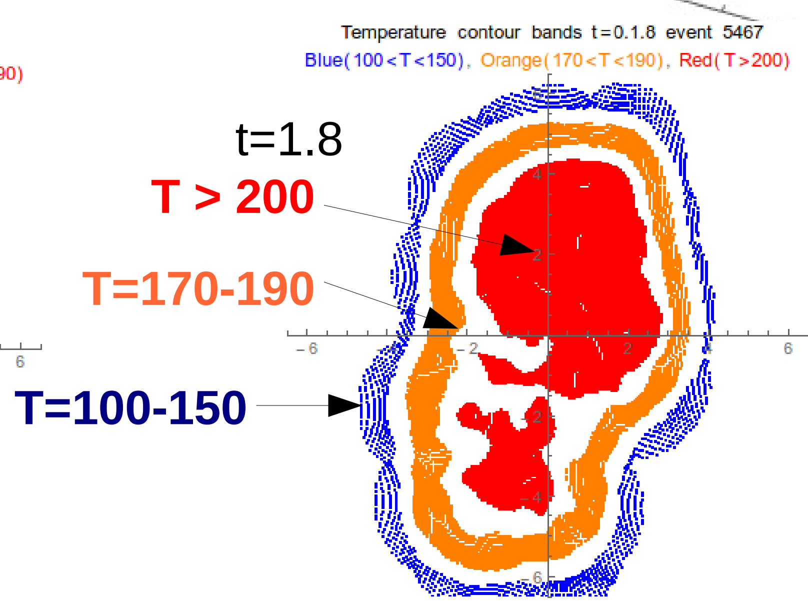
Energy density profile event 5467



Temperature profile event 5467



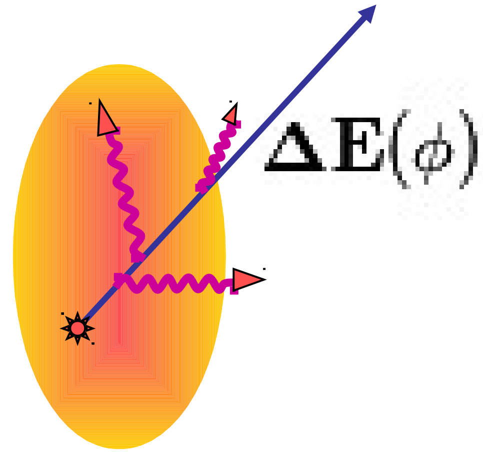


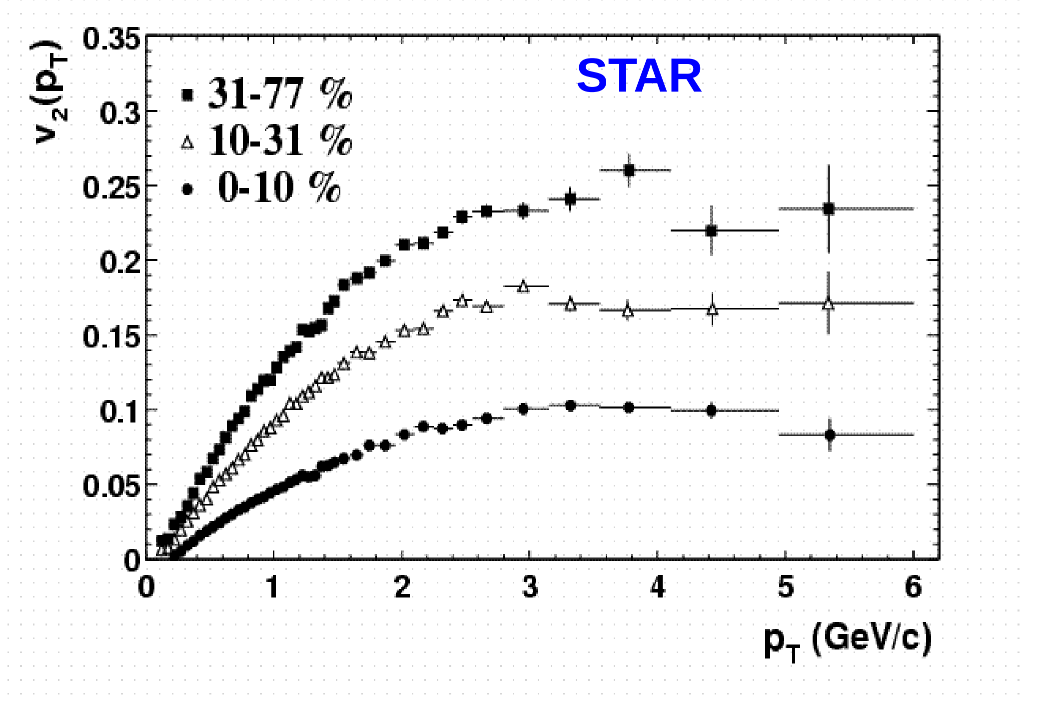


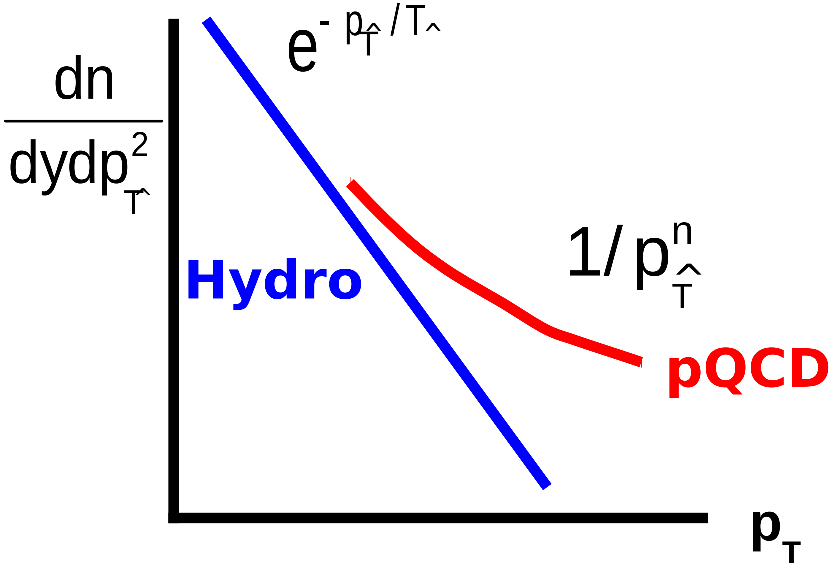
Elliptic Jet Tomography

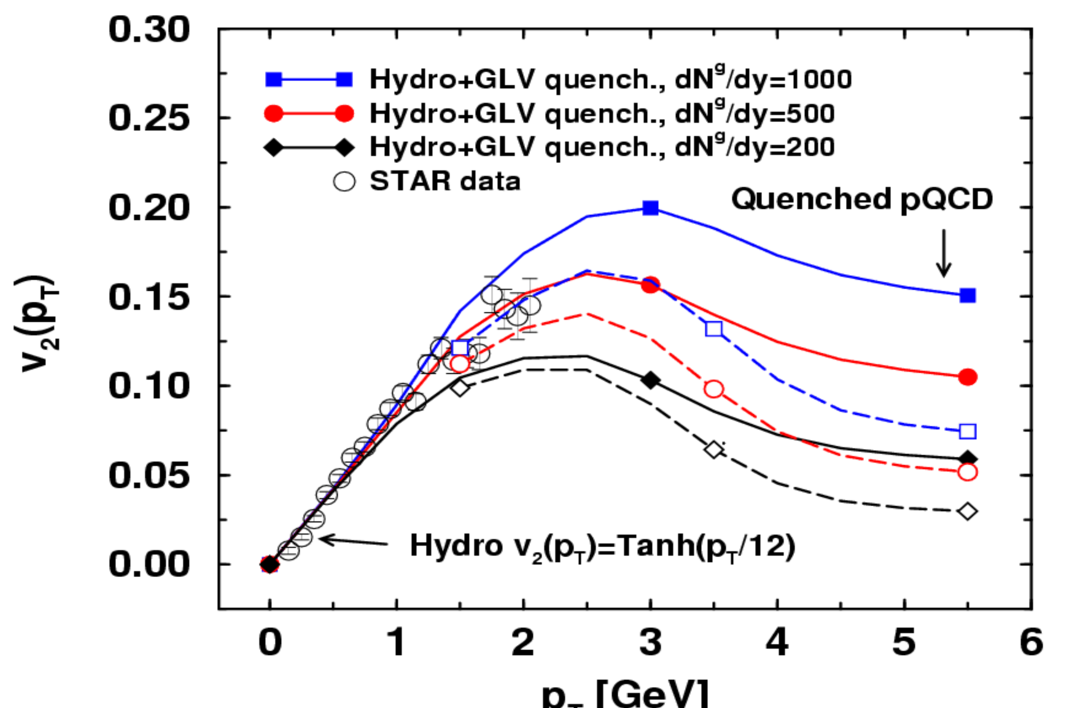
MG, I. Vitev and X.N. Wang, PRL86(01)

$$\rho_{QGP}(\tau, x_0 + \hat{n}\tau)$$





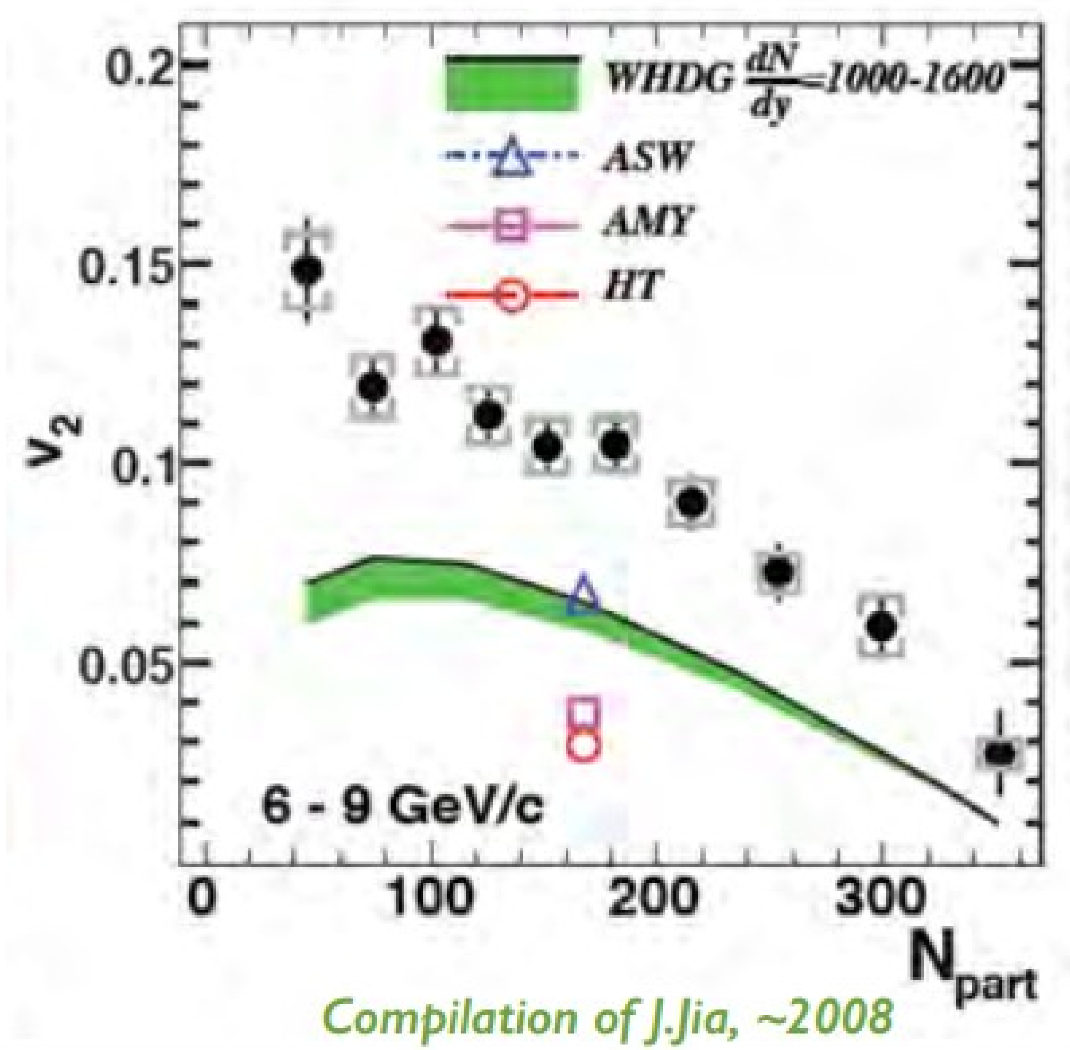




Until recently RAA *and* v2 data
could not be simultaneously fit

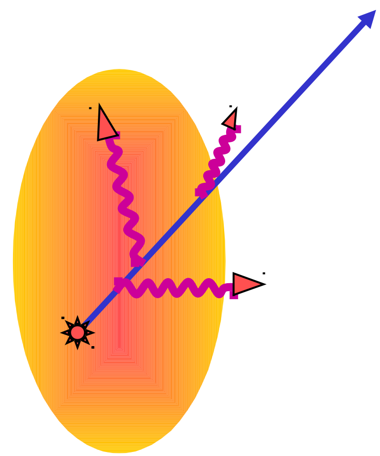
From Jinfeng Liao's Wuhan 2015 talk slide 6

The Jet v2 puzzle of 2008

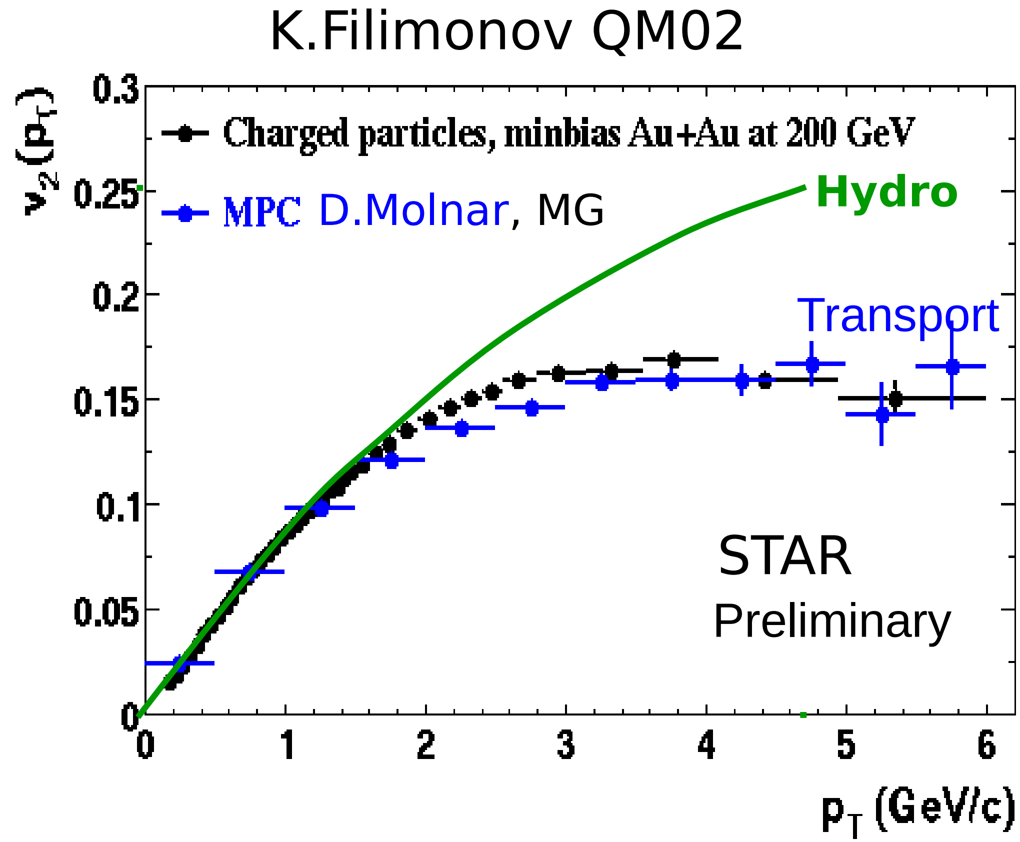


After a lot of work by many groups on jet quenching based on perturbative QCD wQGP picture
The predictions agreed with nuclear suppression of jets $R_{AA}(p_T>5$ GeV), but failed to account for observed azimuthal elliptic asymmetry v2 of pT~ 6-9 jet fragments at all centralities !!

Azimuthal $v_2(p_t)$ Tomography



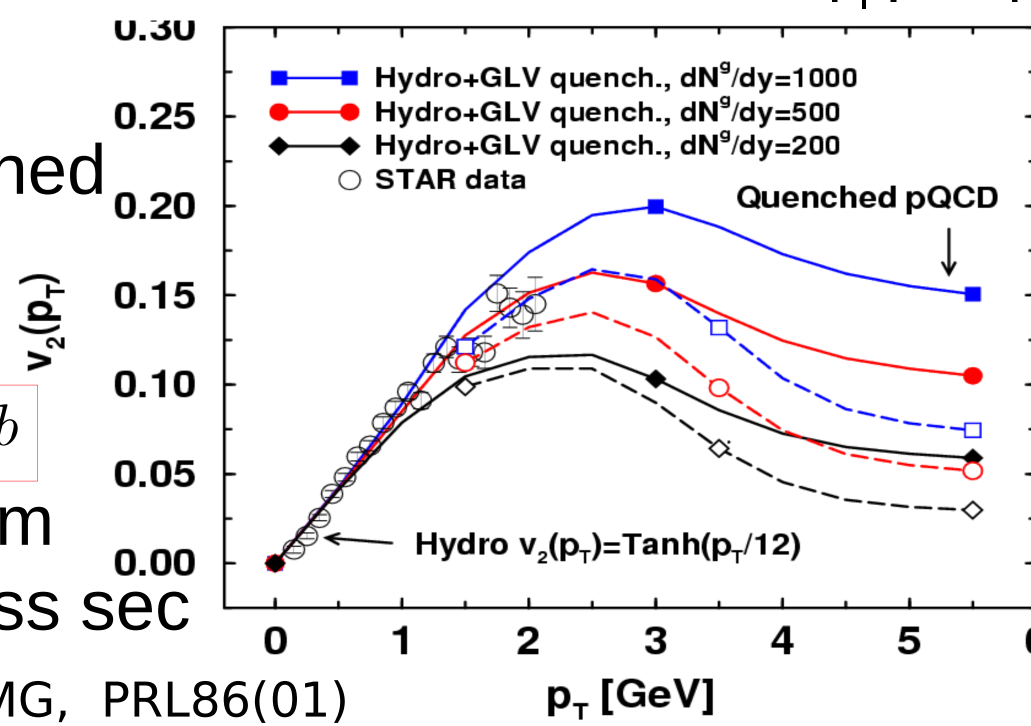
$\rho_{QGP}(\tau, \vec{x}_0 + \hat{n}\tau)$



Deviation from hydro above p_T> 2 GeV/c and approximate Saturation of v_2 can be explained by asymmetric energy loss of jets in noncentral AA

$$\sigma_{transport} \sim 40mb >> \sigma_{pQCD} \sim 2mb$$

High pT v2 is sensitive to geom Eccentricity *and* transport cross sec



I. Vitev, X.N. Wang,MG, PRL86(01)

One provocative solution to the v2 puzzle is that v2 has little to do with multiple interactions

Anisotropic parton escape is the dominant source of azimuthal anisotropy in transport models

Liang He,[1] Terrence Edmonds,[2] Zi-Wei Lin,[3] Feng Liu,[4] Denes Molnar,[1] and Fuqiang Wang[1,4,*]

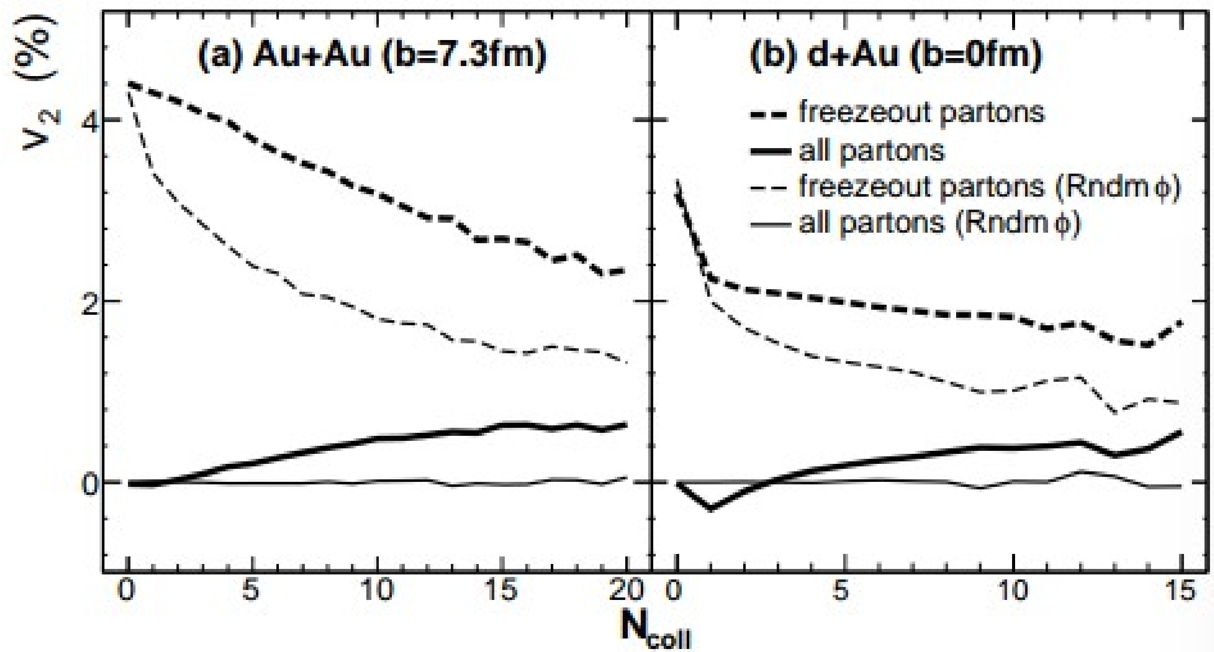
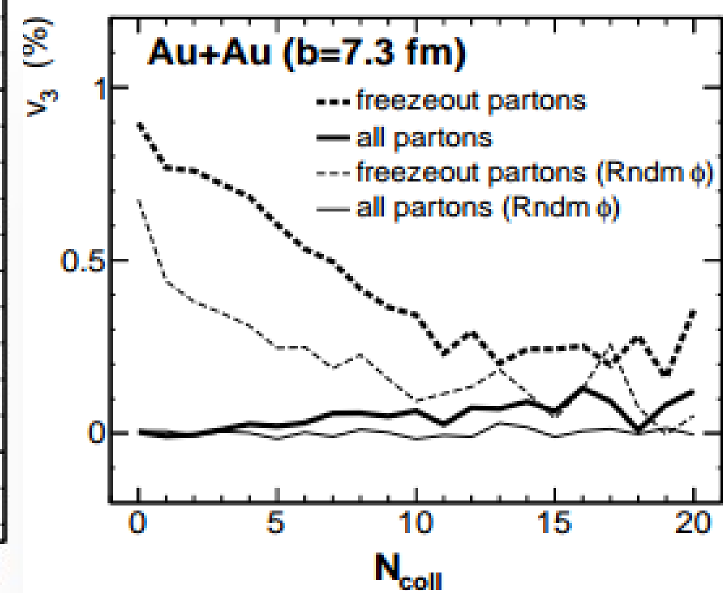


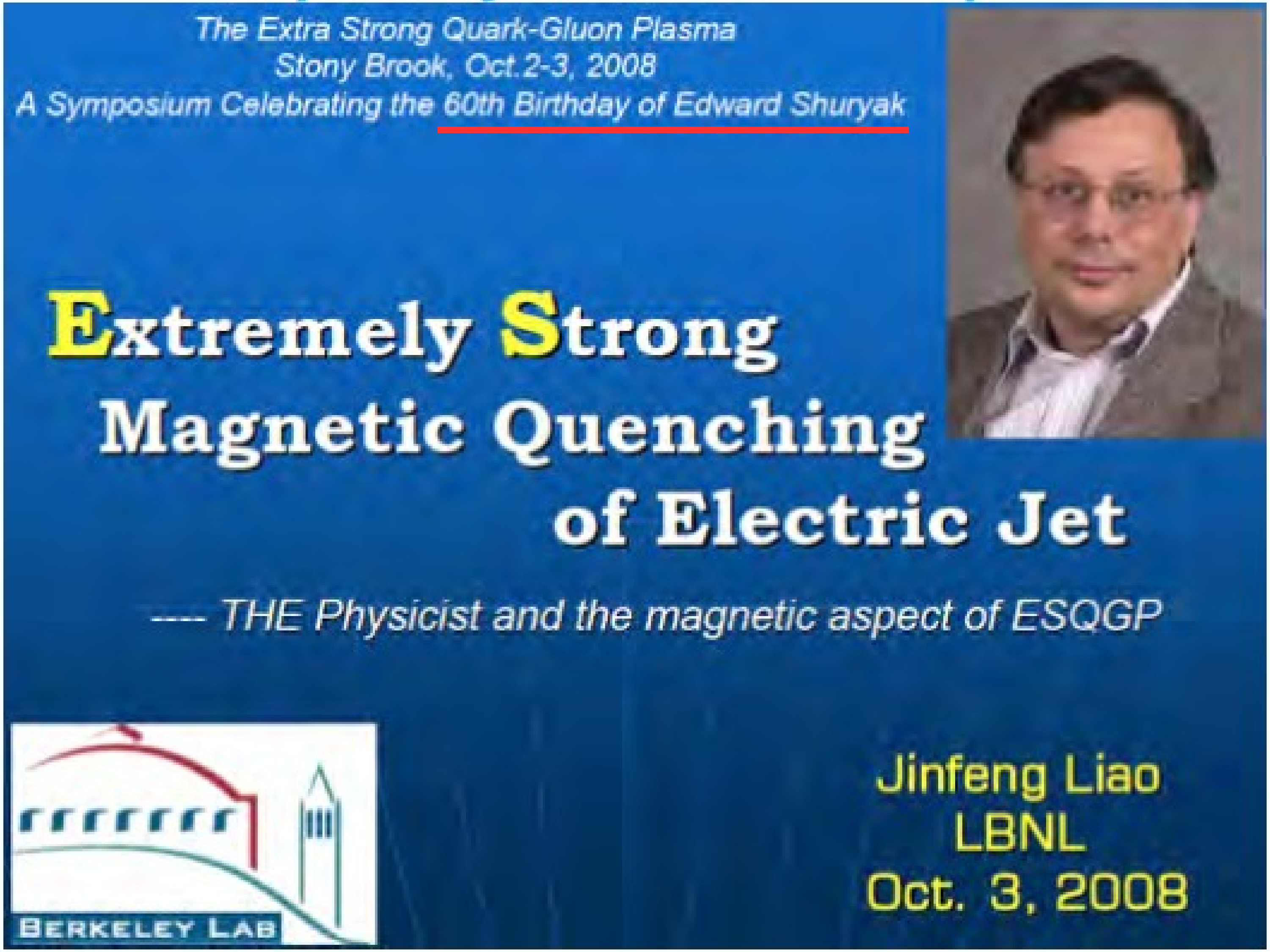
FIG. 5: Parton v_2 as a function of N_{coll} in (a) Au+Au and (b) d+Au collisions. Both normal (thick curves) and azimuth-randomized (thin curves) AMPT results are shown. The solid curves are for all partons after suffering N_{coll} collisions, and the dashed curves are for freezeout partons.



AMPT string melt produces
10 times initial q qbar density
As minijets => need only
Few mb pQCD transport
cross sec!

A more provocative idea in 2007 was

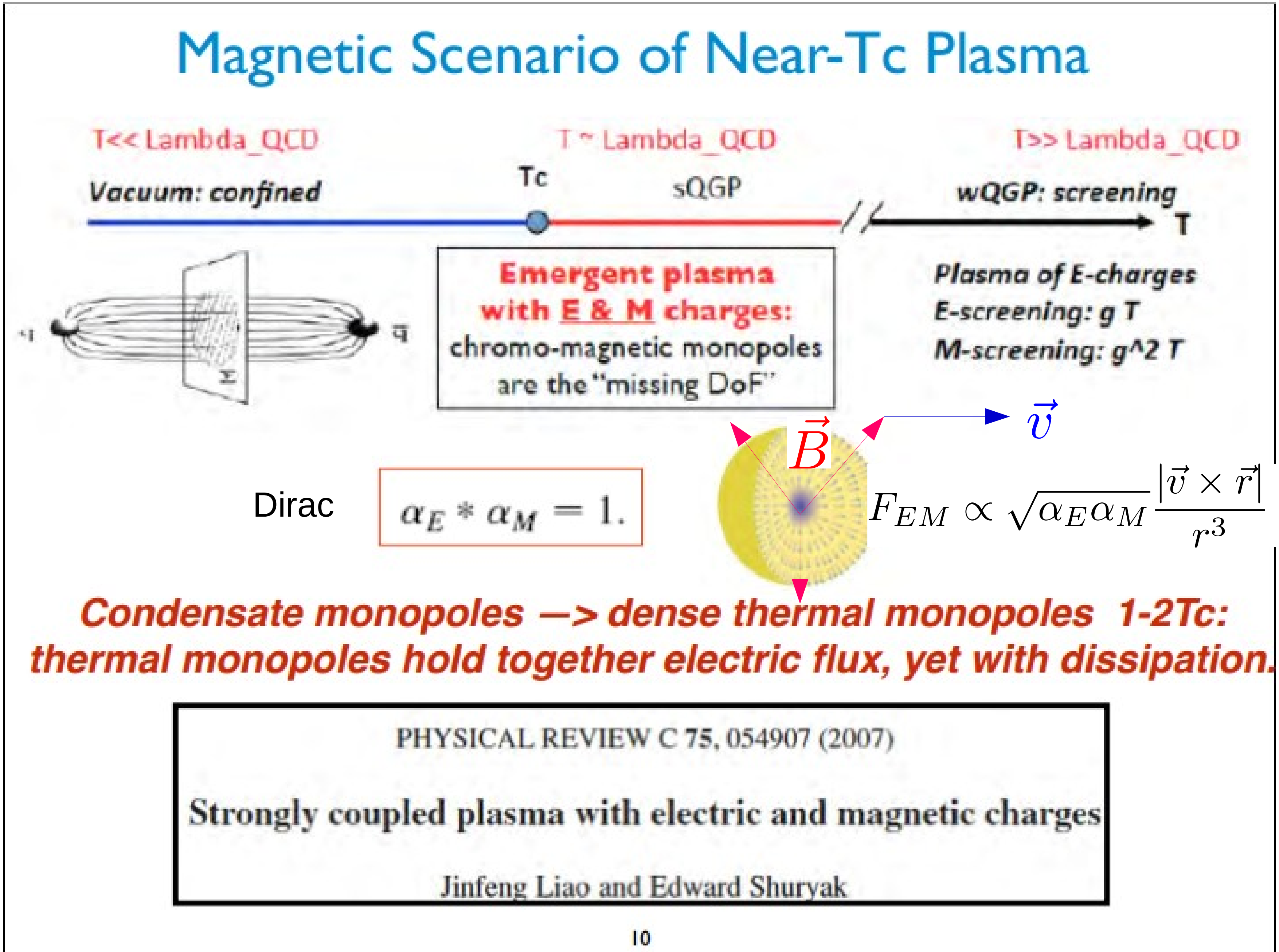
From Jinfeng Liao's CCNU 2015 talk slide 14



JL reported the joint work of Ed and JL (not posted yet at that time), on a novel way of resolving the issue of large jet v2.

[At that time I did not believe ESQGP was needed to solve the v2 puzzle]

Adapted from Jinfeng Liao's Wuhan 2015 talk slide 10



Dirac $\alpha_E * \alpha_M = 1.$

$\vec{B}$ $\vec{v}$

$$F_{EM} \propto \sqrt{\alpha_E \alpha_M}\frac{|\vec{v}\times\vec{r}|}{r^3} \gg \frac{\alpha_E}{r^2}$$

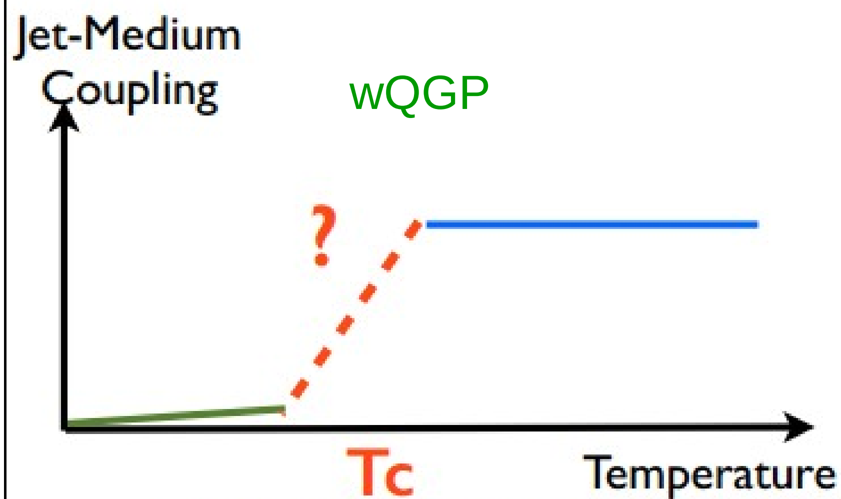
Magnetic Monopole dual superconductor model of color electric confinement

T'Hooft, Polyakov, Mandelstam 40 years ago ?Is the v2 puzzle the first experimental proof ?

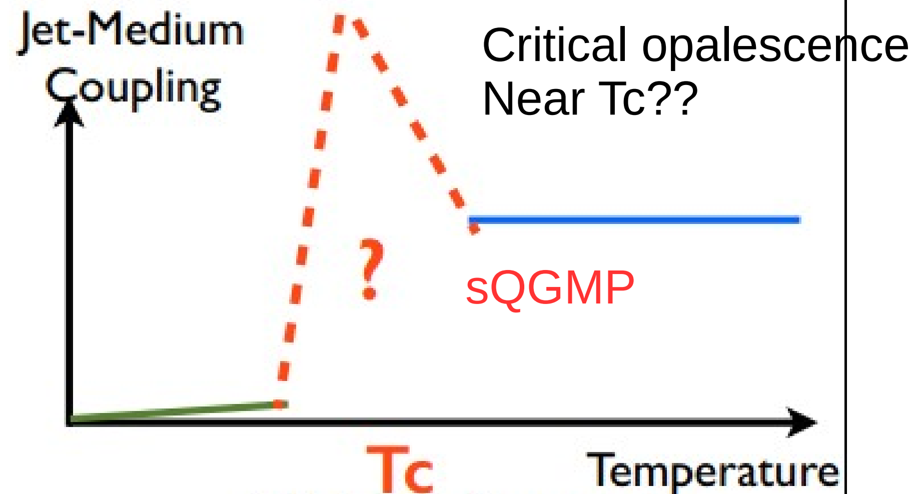
$$\frac{d\sigma_{EM}}{dq_\perp^2} \sim \frac{1}{\alpha^2}\frac{d\sigma_{EE}}{dq_\perp^2} \gg \frac{d\sigma_{EE}}{dq_\perp^2}$$

adapted from JLiao's CCNU 2015 talk slide 15

From "Transparency" to Opaqueness



"Waterfall" scenario



"Volcano" scenario

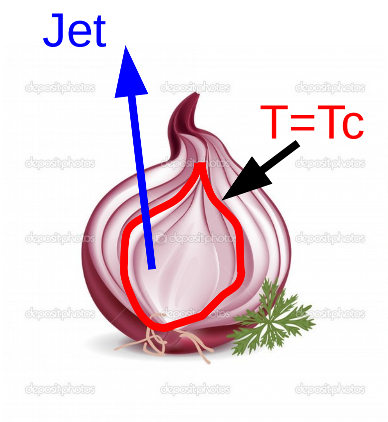
The temperature dependence of jet-medium coupling has profound consequences!

[MG: But is this quantitatively consistent with SPS, RHIC and LHC RAA, v2, v3 data?]

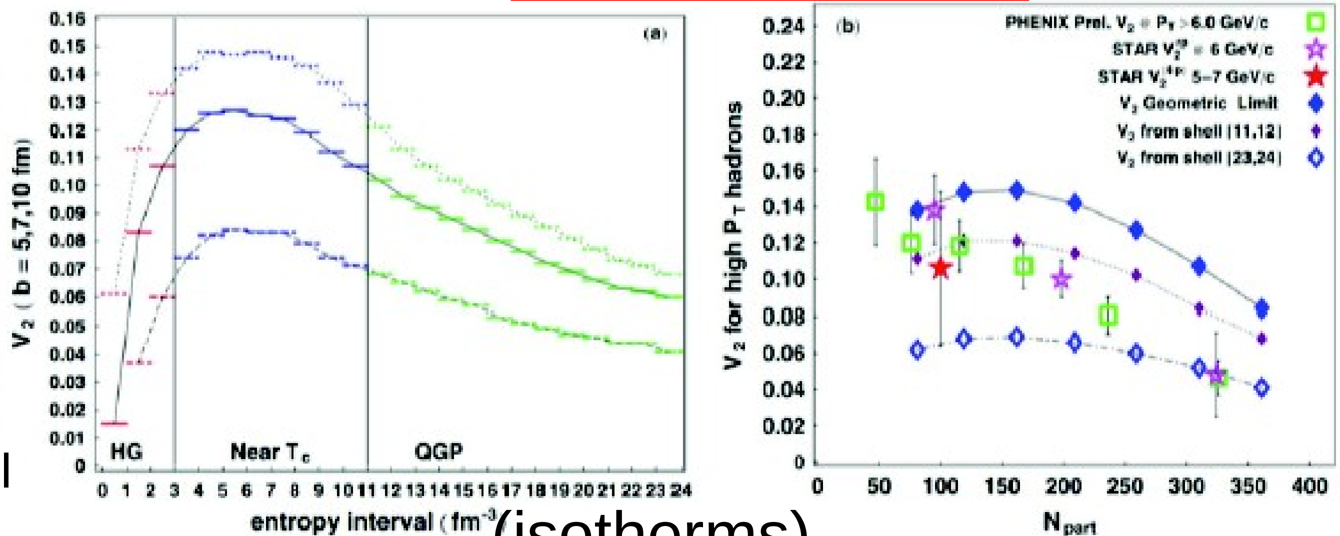
A qualitative solution to the high-p_T v_2 puzzle

Proposed by Shuryak and Liao invoking critical scattering near Tc due to mag monopole conden

(2009)



A Tc "onion" model
With dEdx largest
Near Tc isotherm

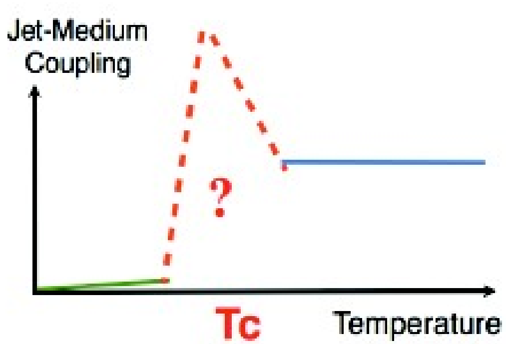


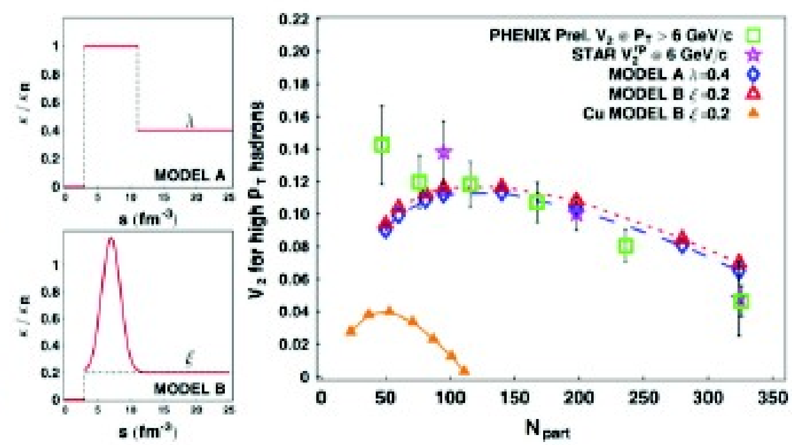
(isotherms)

Figure 3.17: *Left: The v2 obtained for each entropy shell at different centralities. Right: v_2^{max} for high p_T hadrons calculated at different N_{part} compared with available RHIC data.*

Postulate
That jet medium
Coupling peaks
near Tc
Analog of

"Critical Opalescence"





Liao & Shuryak, PRL 2009

Simple optical model estimate appears to "work"

[BBMG verified This solution In 2014]

❖ Origin of the near Tc enhancement? Consistent with lattice and perfect fluidity?

Summary of Lecture 1:

Lattice QCD Thermodynamics Equation of State P(T), S(T)=dP/dT, E(T)=TS-P
Shows gradual "bleaching" of color electric q+g component of the QGP
As t_> Tc ~ 170 from above

Polyakov Loop L(T) and quark susceptibility $\chi_2^u = \frac{\partial^2 (P/T^4)}{\partial (\mu_u/T)^2}$ Lead to different possibilities

The semi-QGP model of color electric composition near Tc depends on

Color liberation schemes

$$\chi_T = \frac{\rho_e}{\rho_{tot}} = \frac{\rho_e}{\rho_e + \rho_m} = \begin{cases} \chi_T^u = c_q \chi_2^u + c_g L^2 \\ \chi_T^L = c_q L + c_g L^2 \end{cases}$$

Fast q, Slow^2 g

Slow q, Slow^2 g

The missing "m" density is fixed by a choice of Liberation Scheme and relation of ρ to EOS

$$\rho_m(T) = (1-\chi(T))\rho_{tot}(T) = (1-\chi(T)) \begin{cases} P(T)/T \\ S(T)/4 \end{cases}$$

The2008 AA v2(pT>5 GeV) puzzle challenged perturbative dEdx models of jet dEdx.
But can be "solved" in various ways.

Is interpreted as density

Most provocative interpretation by J.Liao&E.Shuryak is to interpret ρ_m as density
of emergent color magnetic monopoles near Tc leading to "volcano scenario" for dEdx

In Lecture 2 I review recent progress with CIBJET S.Shi,J.Liao,MG to quantify the above model