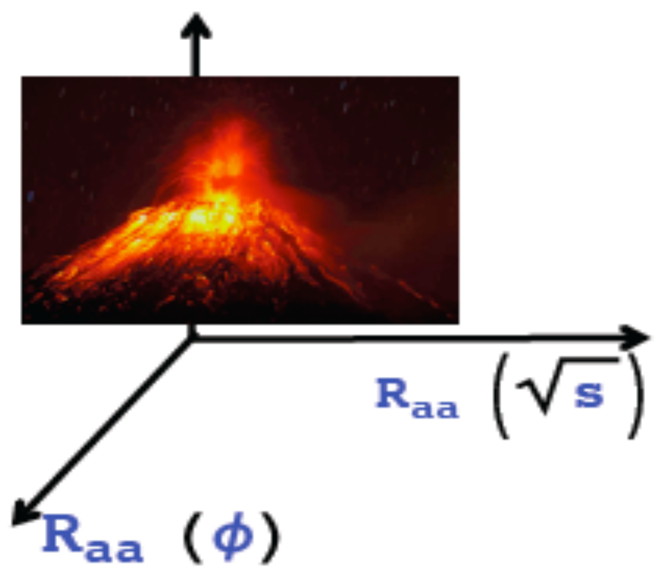
The Geometry of Jet Quenching & the Physics of sQGP



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Research Supported by NSF

Outline

- Confinement, deconfiement, and magnetic scenario
- Temperature dependence of QGP properties
- The geometry of jet quenching
- The semi-quark-gluon monopole plasma (sQGMP)
- Summary

References:
JL & Shuryak,PRC2007,2008;NPA2006;PRD2010;PRL2008,2012.
J. Xu, JL, M. Gyulassy, arXiv: 1411.3673.
X. Zhang, JL, PRC2013,2014;PLB2012.
JL, Shuryak, Phys.Rev.Lett. 102 (2009) 202302.

“The Missing Particles"

Free Quark Searches

from PDG 2014

All searches since 1977 have had negative results.

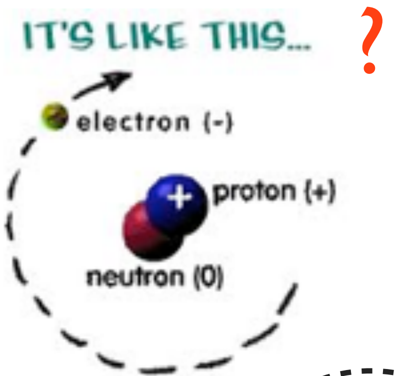
This null result is by itself a most remarkable FACT of Nature.

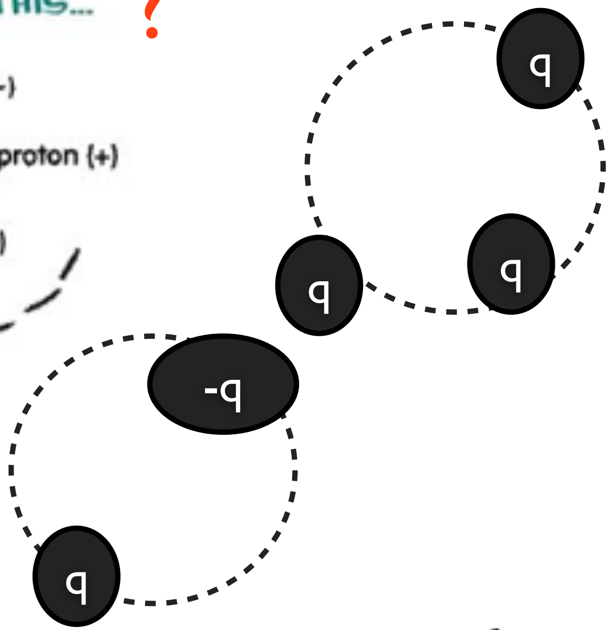
“Truth is stranger than fiction, but it is because fiction is obliged to stick to possibilities: truth isn’t."

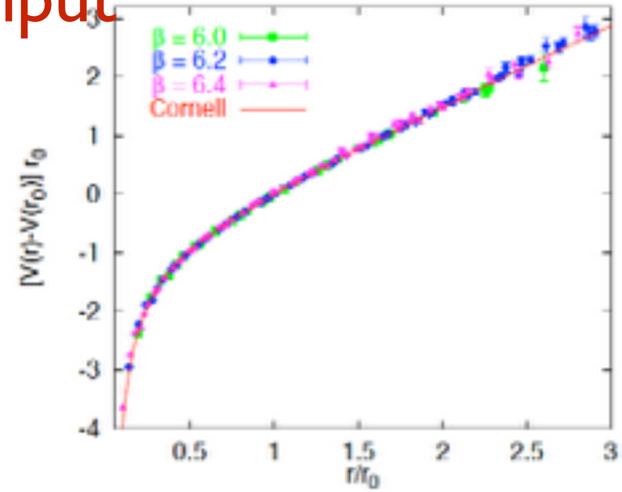
How do we know the “unobservable”quarks are there?
Why? This is interesting!

Hadrons as "Quark-Atoms" and as Strings

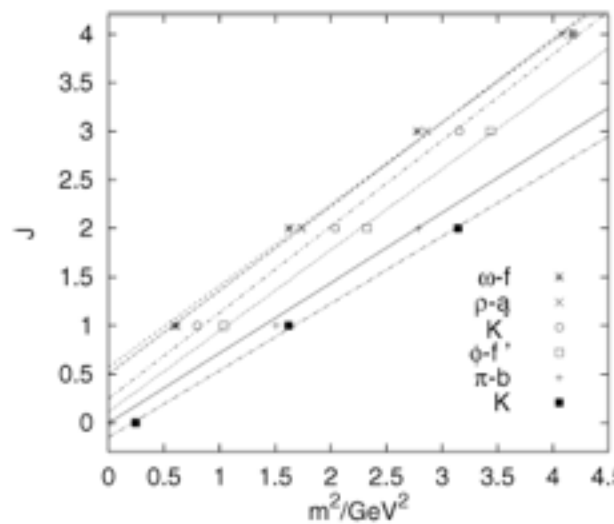
Quark model: POTENTIAL V(r) as input

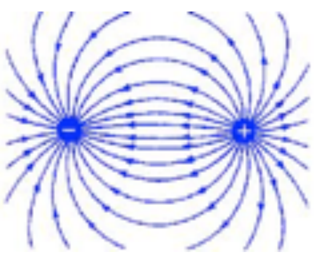




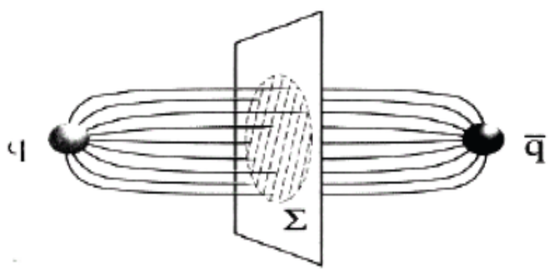


At large distance / high excitations: hadrons are like strings





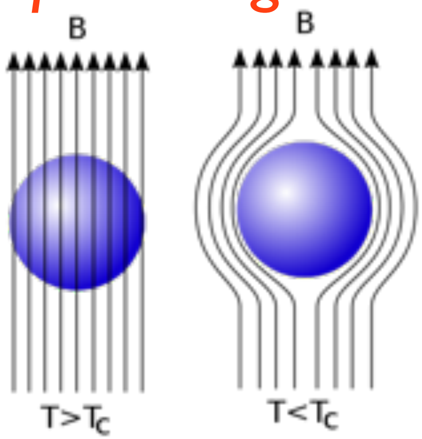
QED dipole field



QCD dipole field

Meissner Effect in Superconductor

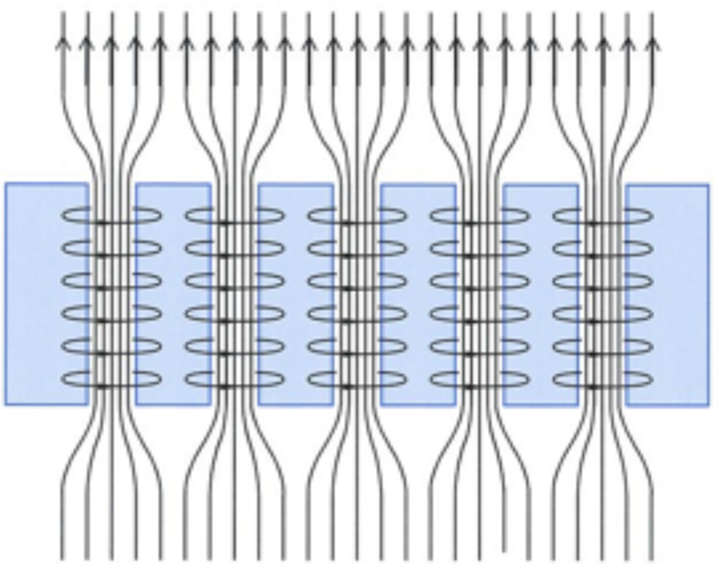
Meissner effect: electric (cooper-pair) condensate expels magnetic fields, and squeezes them into flux tube.

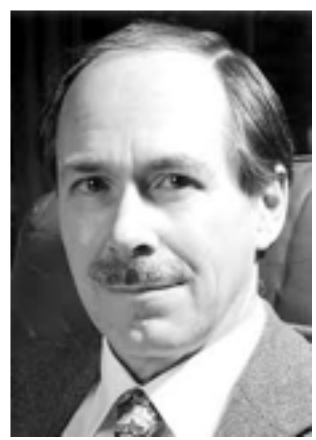


$$\mathbf{j}_s = -\frac{n_s e^2}{mc}\mathbf{A}.$$ **(London equation)**

$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c} \qquad \nabla^2 \mathbf{B} = \frac{1}{\lambda^2}\mathbf{B}, \qquad \lambda \equiv \sqrt{\frac{mc^2}{4\pi n_s e^2}}.$$

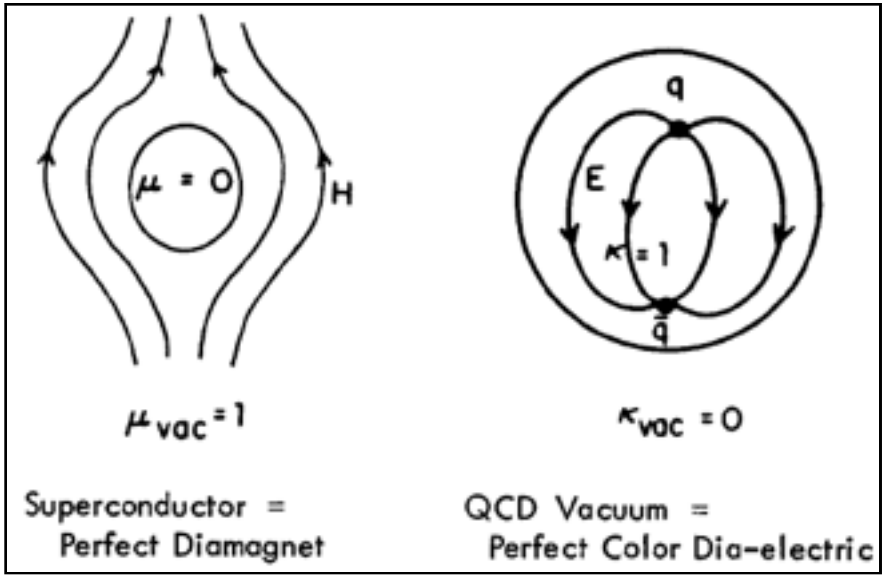
$$\longrightarrow \quad B_z(x) = B_0 e^{-x/\lambda}.$$





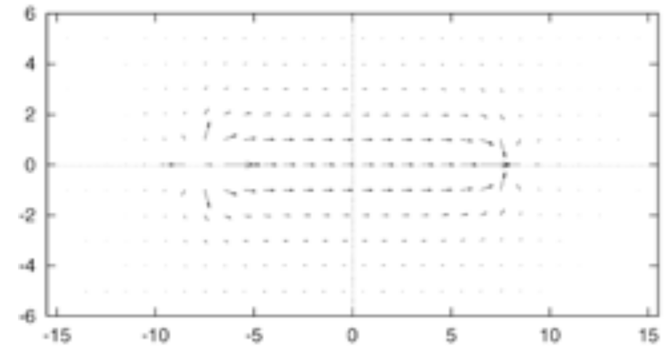
’t Hooft, Mandelstamm, Nambu
—> transforming this insight into QCD

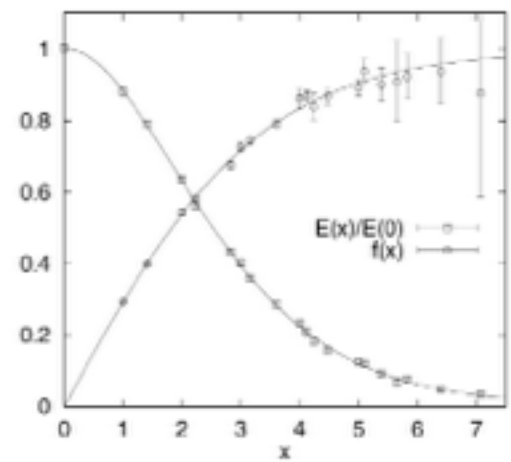
QCD Vacuum as Dual Superconductor



QED Superconductivity		QCD Vacuum as a Perfect Color Dielectric
$\vec{H}$	⟷	$\vec{E}$
$\mu_{inside} = 0$	⟷	$\kappa_{vacuum} = 0$
$\mu_{vacuum} = 1$	⟷	$\kappa_{inside} = 1$
inside	⟷	outside
outside	⟷	inside

Lattice gauge theory shows the formation of flux tube.





Dual Abelian-Higgs Model was developed as effective description of QCD vacuum.

But what is the "magnetic condensate"? Where does it come from?

Magnetic Monopole & Dirac Quantization

Classical Electrodynamics with E & M sources :
(considered by J.J. Thompson as early as at 1896)

$$\nabla \cdot \mathbf{D} = \rho_e, \qquad \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_e$$

$$\nabla \cdot \mathbf{B} = \rho_m, \qquad -\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} + \mathbf{J}_m$$

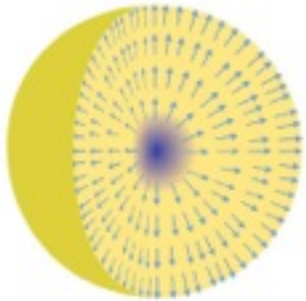
Monopole: source of long range Coulomb magnetic field.
E & M on equal footing!

Dirac (1931): is such electrodynamics with both E & M sources compatible with **quantum mechanics**?

Dirac : e*g = 1

Magnetic Monopoles & E-M Duality

't Hooft-Polyakov (1974):
monopoles naturally arise as topological solutions
to classical EoM in non-Abelian gauge theories;
Dirac Quantization obeyed, mass & size ~ 1/g



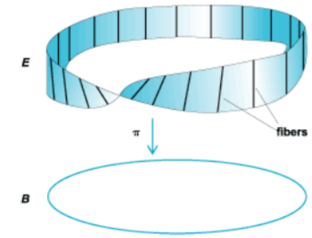
$$\text{Dirac}: e^{*}g = 1$$

What happens if the gauge theory with monopoles is in strongly coupled regime?

E-M Duality: (Motonen, Olive, 1977)
strong coupling → change of D.o.F. toward emergent ones ;
Dirac condition → E and M couplings inversely related
E weakly coupled → theory in terms of E language
E strongly coupled → theory better described by Magnetic.

The classical work by Seiberg-Witten (1994) for N=2 SYM:
All work in this way, including the confinement !

How are Monopoles Made?



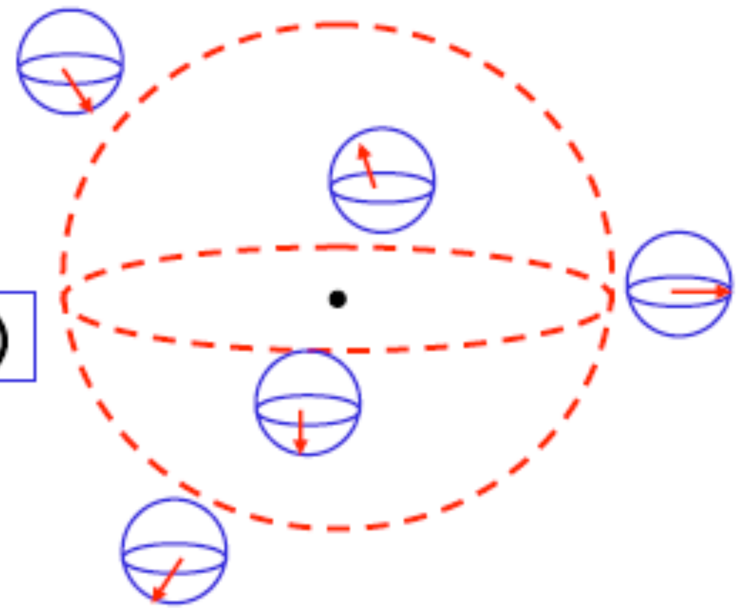
Möbius strip, the simplest nontrivial example of a fiber bundle

’t Hooft-Polvalov monopole in George-Glashow model with SU(2)

$$L = -\frac{1}{2}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + \mathrm{Tr}\, D_\mu\phi D^\mu\phi - V(\phi)$$ with higgs-type condensate

$$|\vec{\mathbf{x}}| \longrightarrow \infty$$

$$|U\Phi U^{-1}| = v \neq 0$$



Mapping : $S^2 \longrightarrow SU(2)$

↓

Topological charge &
Magnetic charge

$$g = \frac{4\pi n}{e}, \qquad n \in \mathbb{Z}$$

BPS limit:
V → 0

In QCD it is A_0 that can play the role of the adjoint scalar.
This is evident in hight-T dimensional reduction.

Important Features

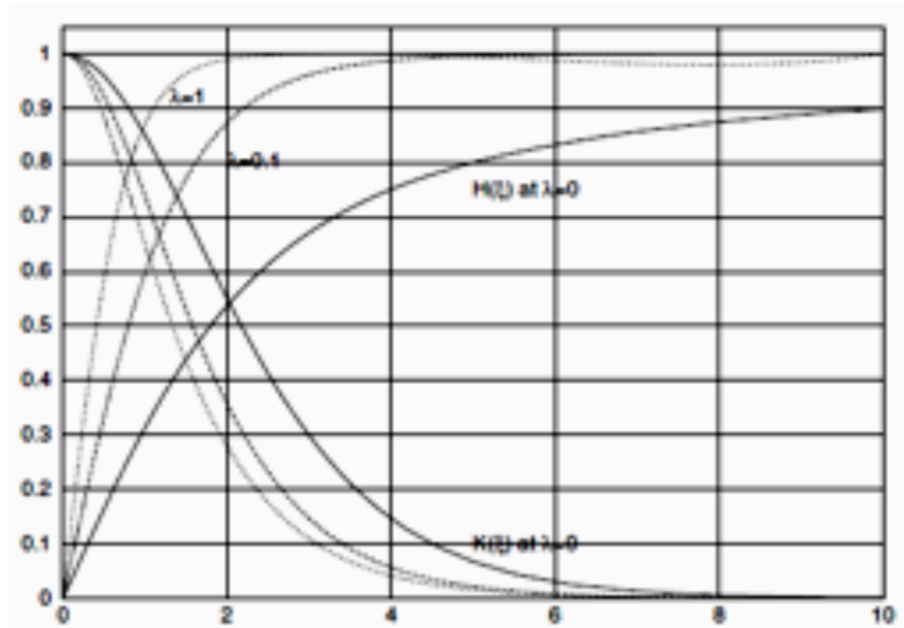
In the Higgs phase with VEV to be v:

Gluons → $M_W = e * v$

Higgs → $M_H \sim v * \lambda$

Monopoles→ $M_m = g * v$

M-core → size: $R \sim \dfrac{1}{e * v}$

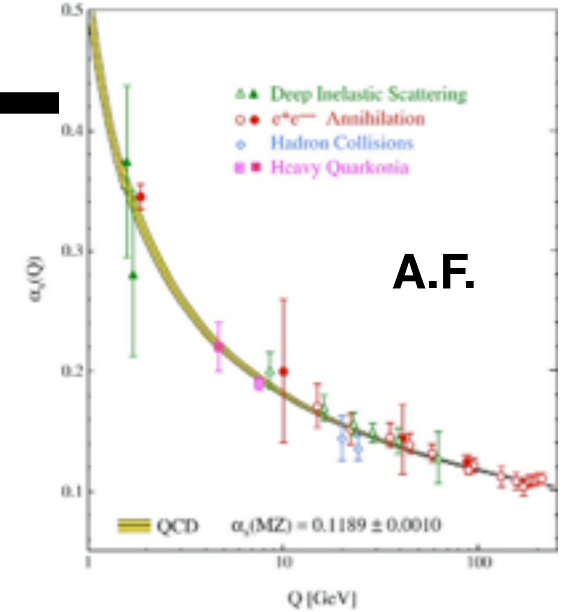


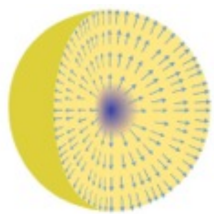
BPS Limit:
\lambda→0 completely flat in Higgs VEV;
Higgs becomes massless;
M-M interaction becomes zero.

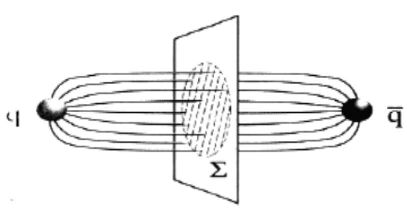
At strong coupling, they become the light, and well localized objects ("particles" if you like), being the emergent and dominant D.o.F.

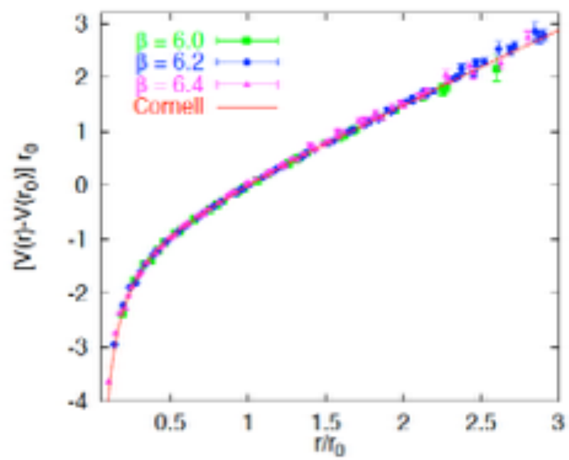
A Plausible Picture for QCD Vacuum

very strong coupling
at low energy
—> emergent monopoles
—> vacuum mag. condensate









Regge phenomena;
Veneziano amplitudes;
Lund model,
string fragmentation;
...

flux tube, linear potential,
and stringy hadrons

What happens If we heat up the Vacuum?

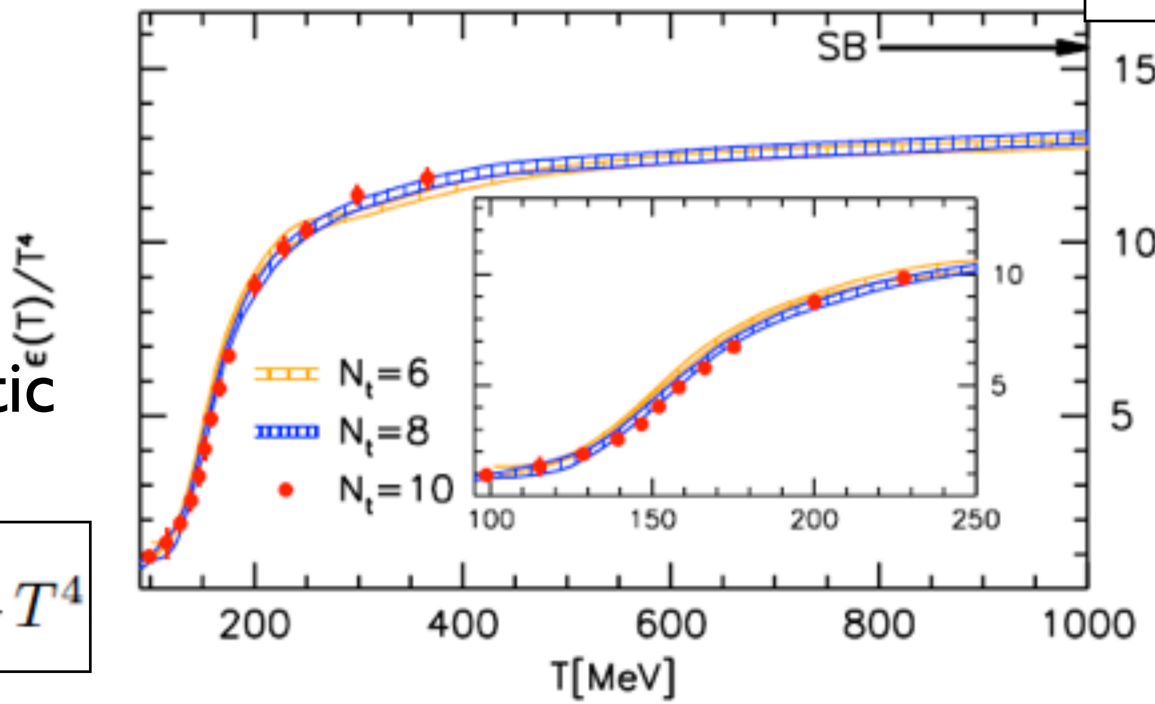
Thermodynamic Transitions

from Lattice QCD (Wuppertal-Budapest)

RHIC LHC

$$\epsilon = 47.5 \times \frac{\pi^2}{30} T^4$$

free QGP



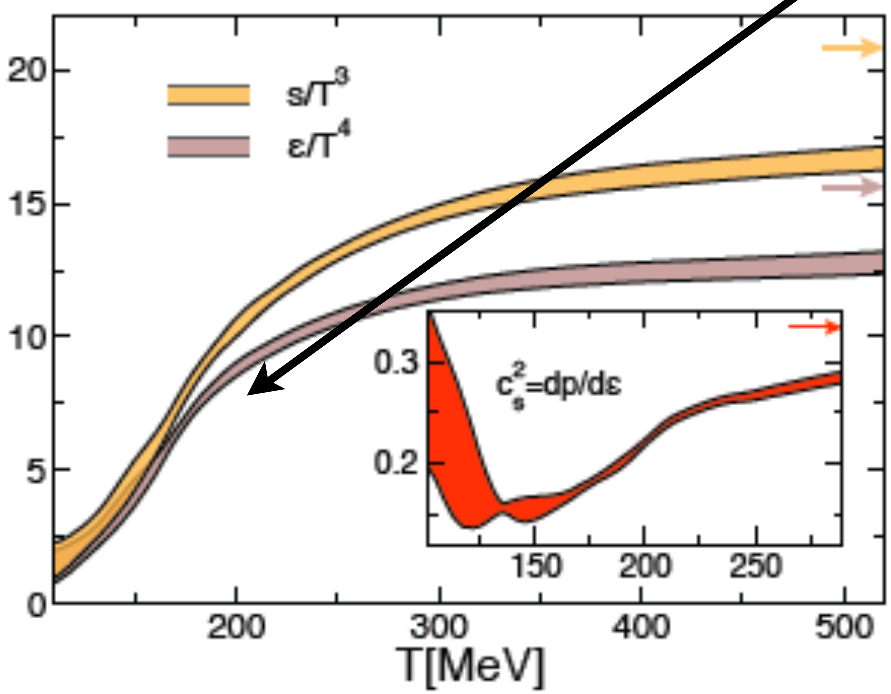
a relativistic pion gas

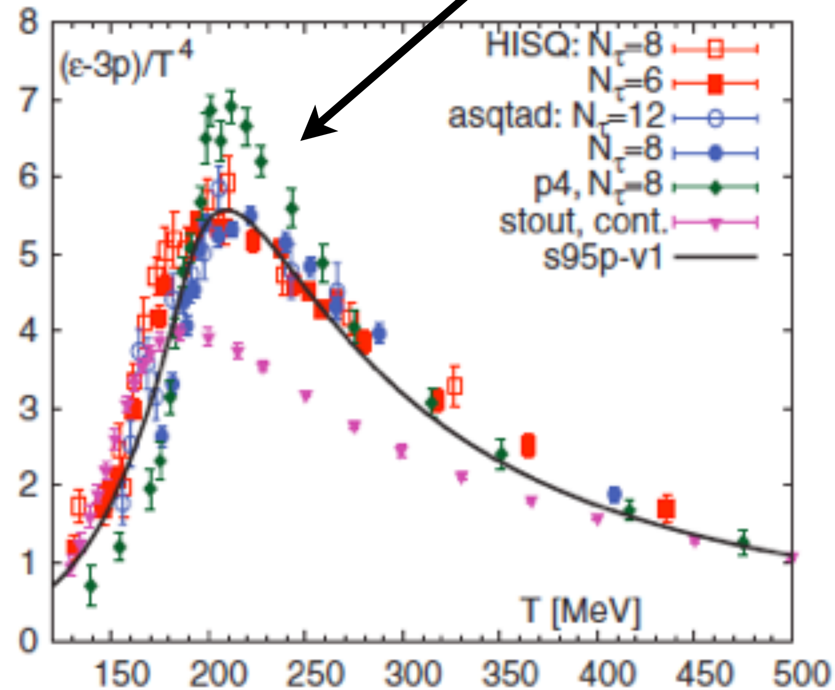
$$\epsilon = 3 \times \frac{\pi^2}{30} T^4$$

More precisely,
Hadron Resonance Gas

* Two benchmarks at low/high T
* A transition regime in the middle
* Crossover (instead of a phase transition)

Hot off the Lattice: Crossover, but Rapid



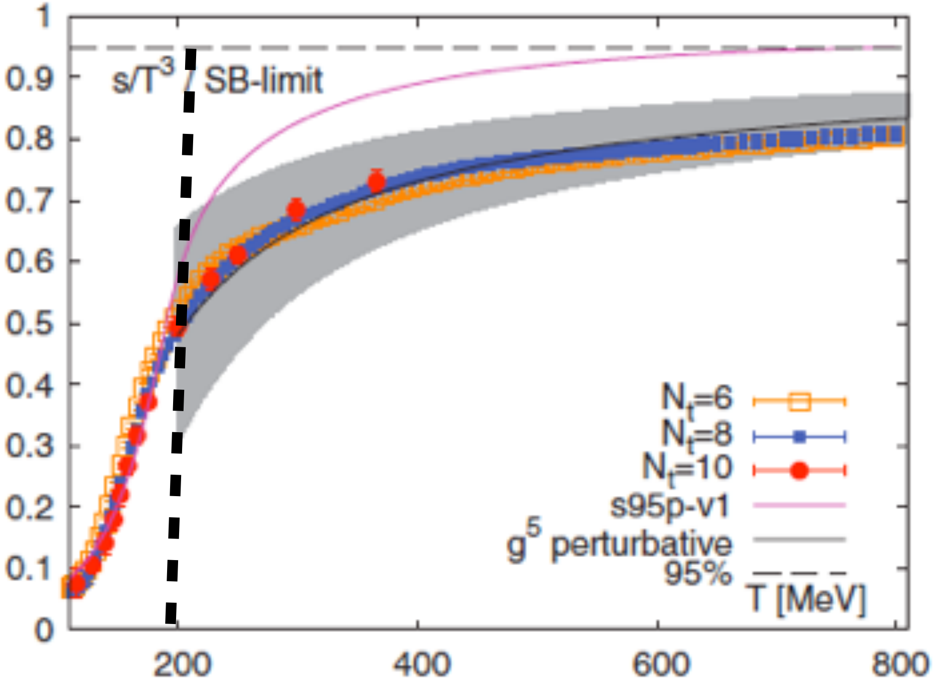


"Rapid Up" or "Rapid Down":
pressure/energy density/entropy density/
2-nd q-susceptibilities/
chiral condensate/Q-bar-Q free energy/...

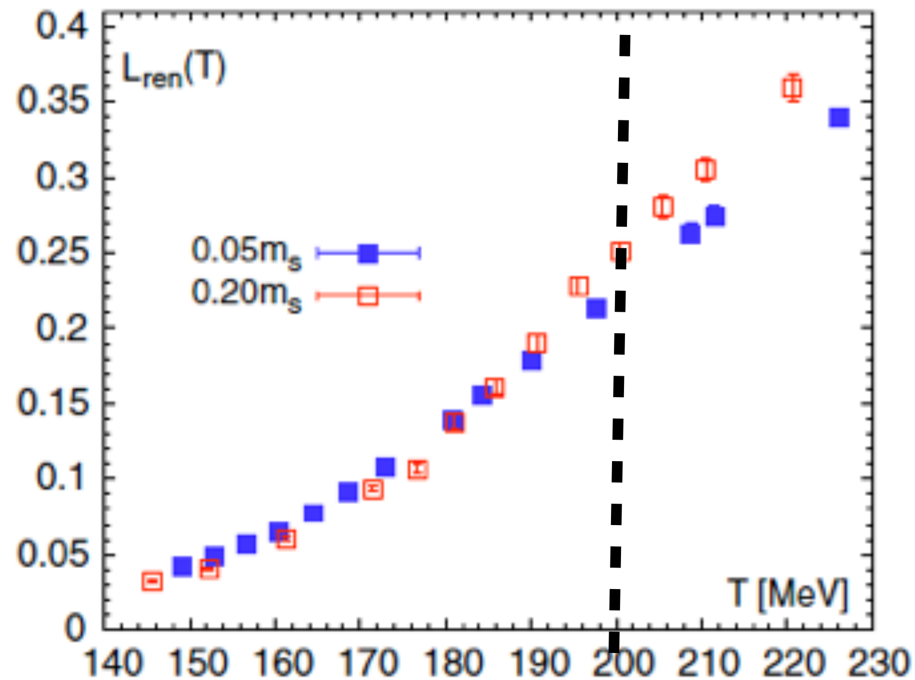
"Peak" or "Dip":
trace anomaly/chiral susceptibility/
4-th q-susceptibilities/
Q-bar-Q internal energy/
speed of sound//...

Liberation of Color? Missing DoF?

Degrees of freedom



Degree of color liberation



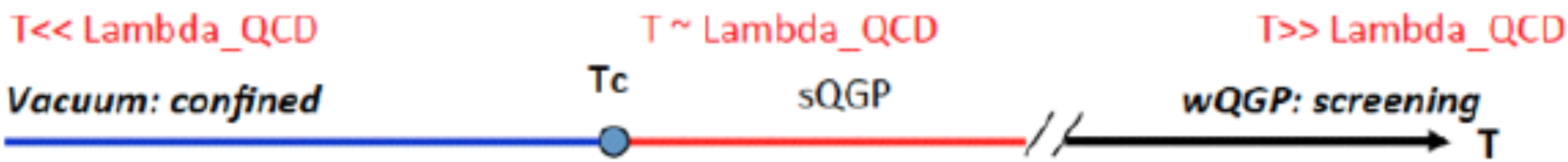
A region around Tc with liberated degrees of freedom but only partially liberated color-electric objects.

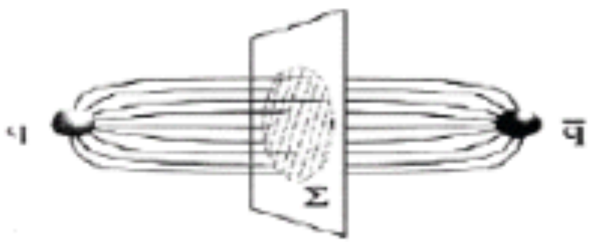
(Pisarski & collaborators: semi-QGP)

Then what are the "extra" dominant DoF here???

Thermal monopoles evaporated from vacuum condensate!

Magnetic Scenario of Near-Tc Plasma

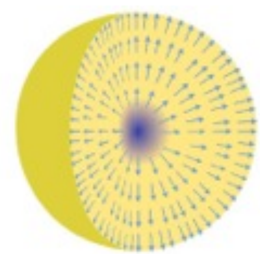




Emergent plasma with E & M charges:
chromo-magnetic monopoles are the "missing DoF"

Plasma of E-charges
E-screening: g T
M-screening: g^2 T

$$\alpha_E * \alpha_M = 1.$$



Condensate monopoles —> dense thermal monopoles 1-2Tc: thermal monopoles hold together electric flux, yet with dissipation.

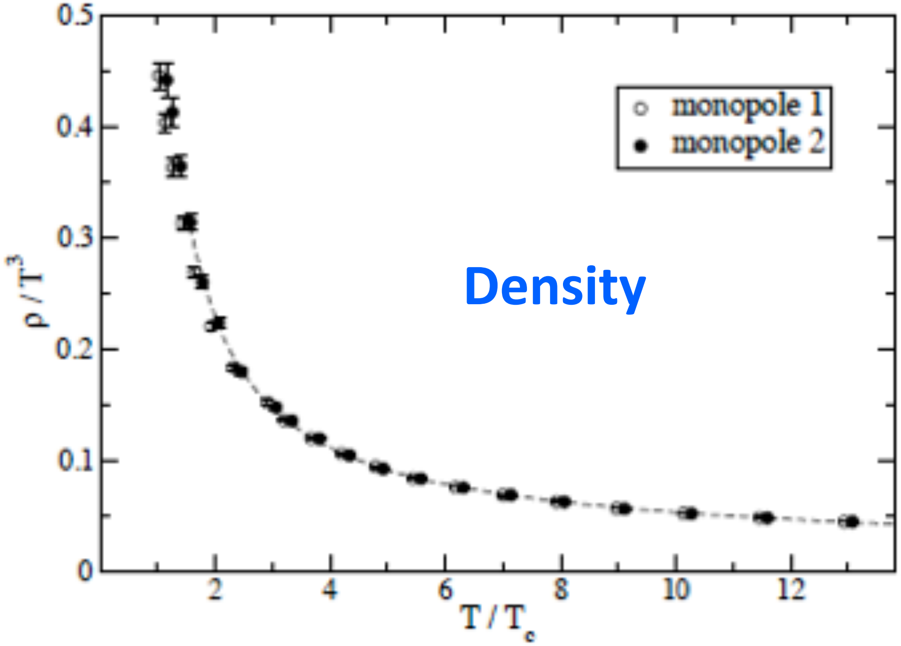
PHYSICAL REVIEW C 75, 054907 (2007)

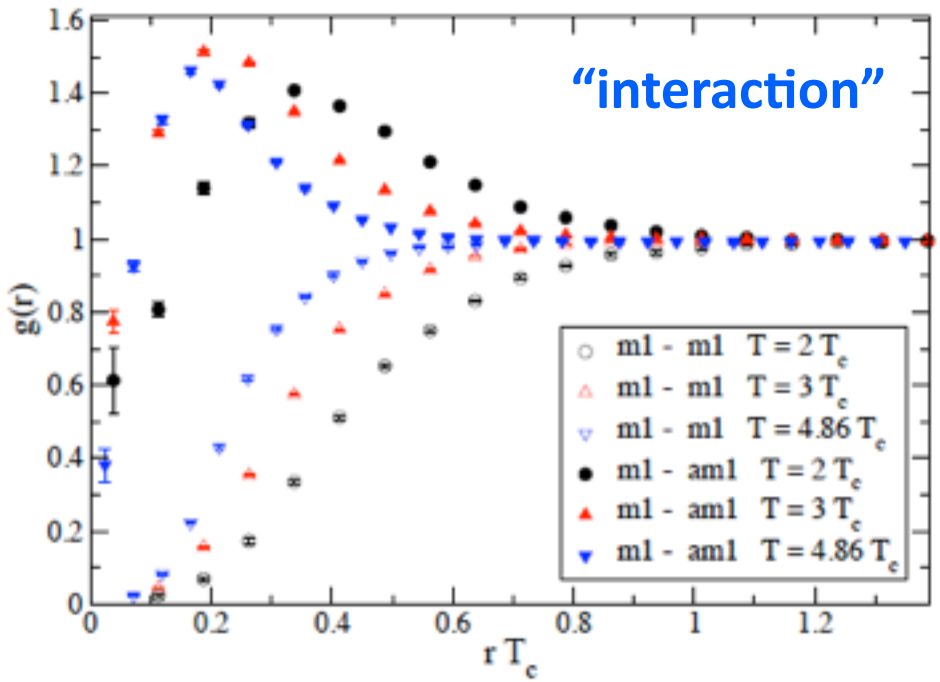
Strongly coupled plasma with electric and magnetic charges

Jinfeng Liao and Edward Shuryak

Lattice Evidence

for SU(3) pure gauge theory
Bonati & D'Elia, arXiv:1308.0302[hep-lat]

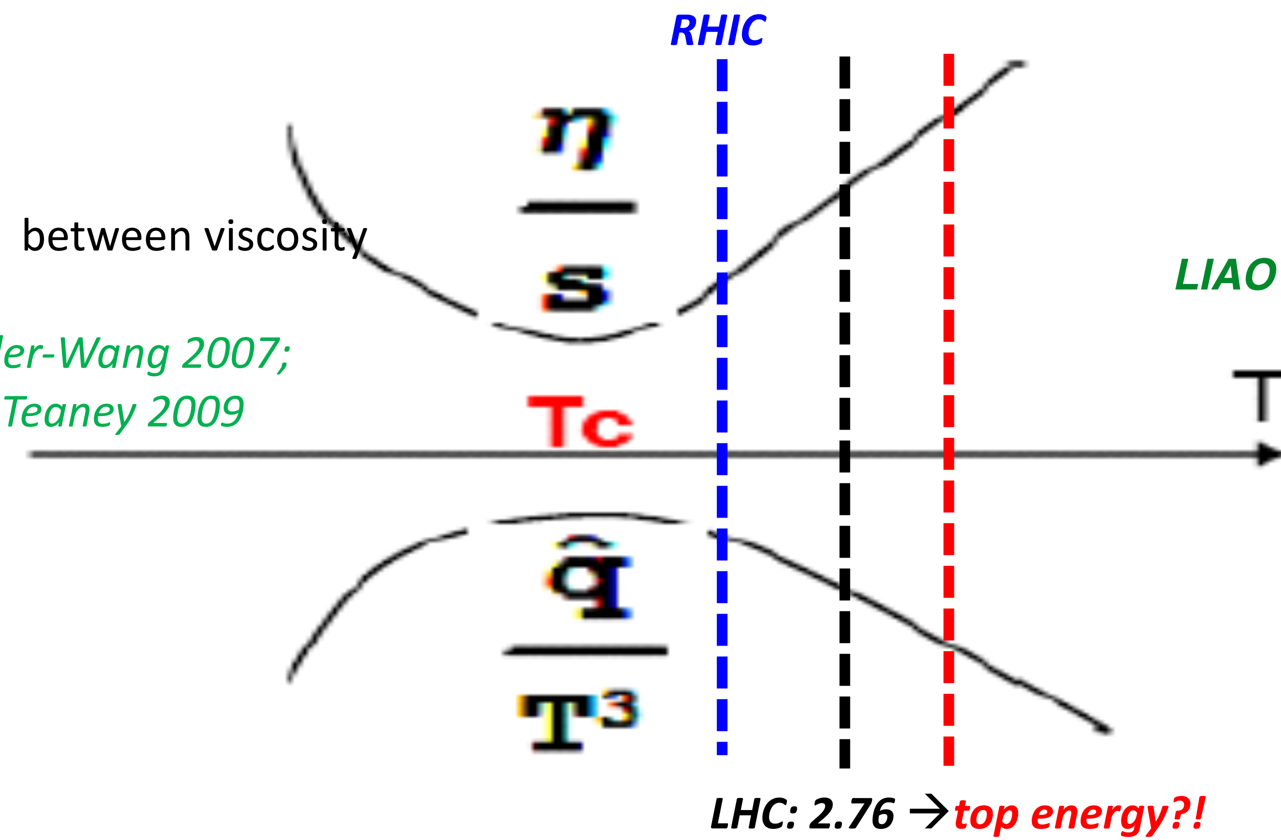




What Does That Imply for QGP Properties?

Near-Tc Matter is Special

Inverse relation between viscosity and opacity
Majumder-Muller-Wang 2007;
Dusling-Moore-Teaney 2009



LIAO@DNP11

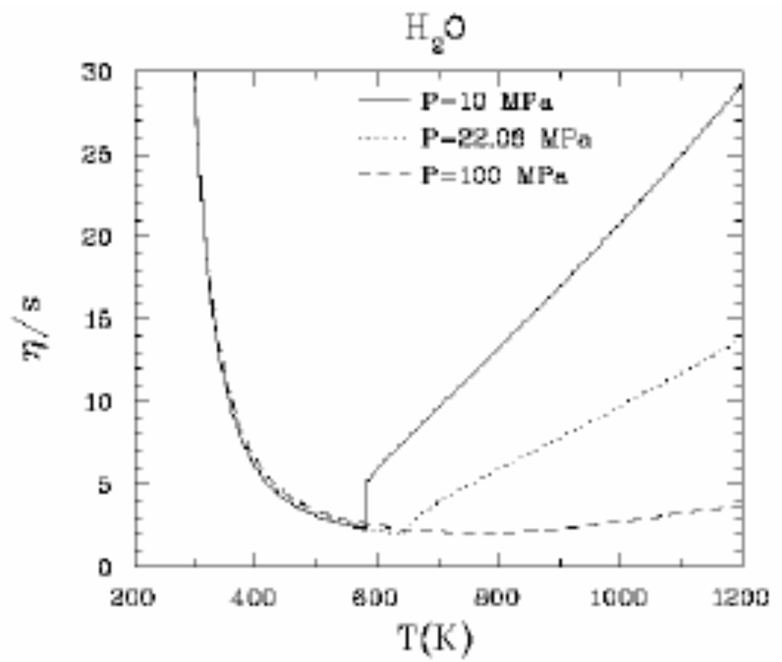
Will we see a systematic deviation from RHIC to LHC? Yes!

The "see-saw"-QGP expects such a picture to occur in a narrow regime 1-3Tc.

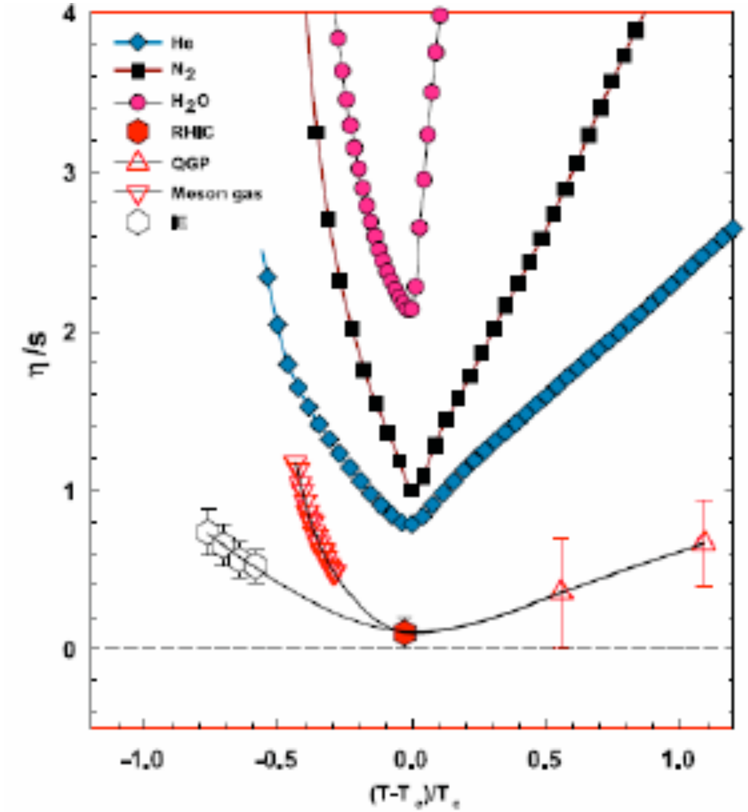
A kind of "critical opalescence"!

Reminiscence of a phase transition underlying the crossover

The "Perfect-ness" of Fluid?

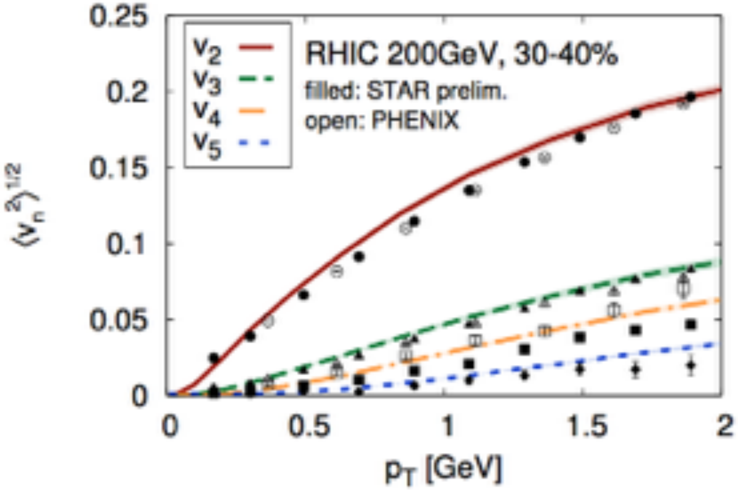


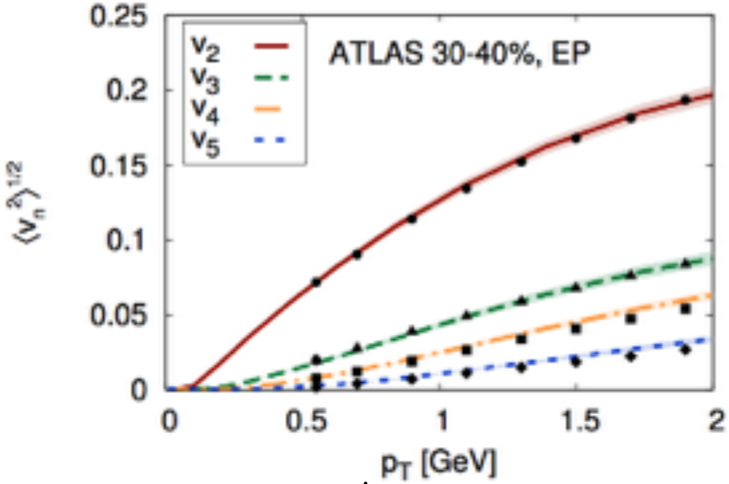
Csernai,Kapusta,McLerran, PRL(2006)



Lacey, et al, PRL(2007)

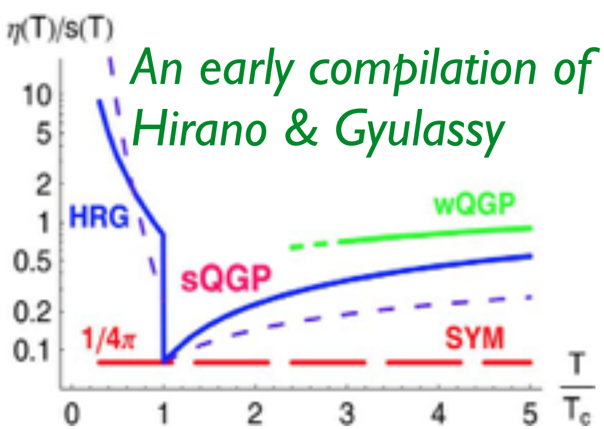
The QGP Liquidity is Shifting!





$$\eta/s \approx 0.12 \longrightarrow \eta/s \approx 0.2$$

Works of multiple groups (BNL-McGill, Frankfurt, Scalay, OSU) consistently suggest a visible increase, ~40%, of average eta/s from RHIC to LHC.

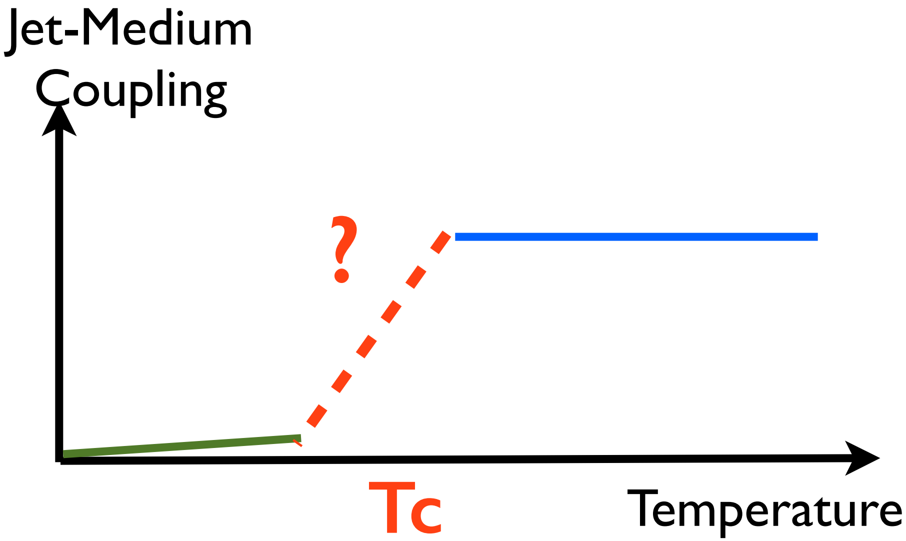


An early compilation of Hirano & Gyulassy

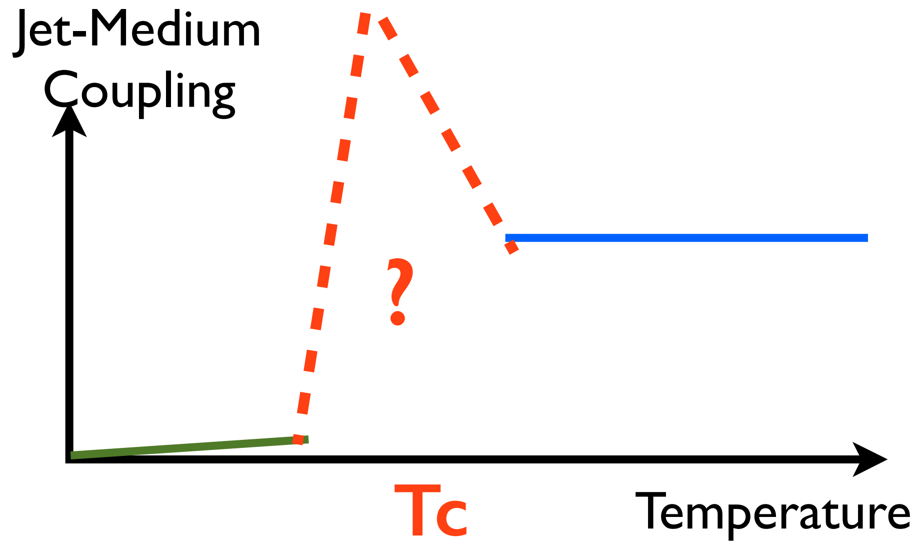
To be in context: the temperature is increased only by ~30% from RHIC to LHC.

Such rapid change is an indication of near-Tc phenomenon.

From Transparency to Opaqueness



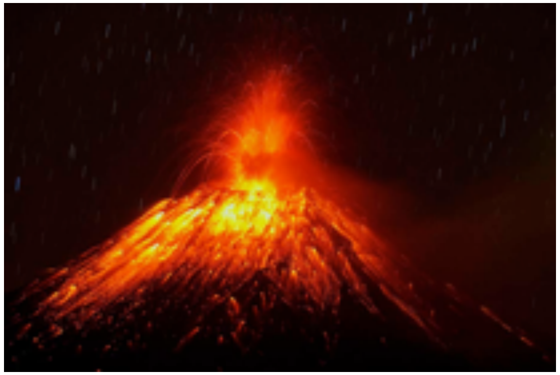
“Waterfall” scenario



“Volcano” scenario

To me, this is a question of fundamental interest in order to understand jet-quenching & the medium itself.

V.S.



How can we get the answer about the T-dependence of jet-medium interaction?

Do we even have a chance to find out the answer?

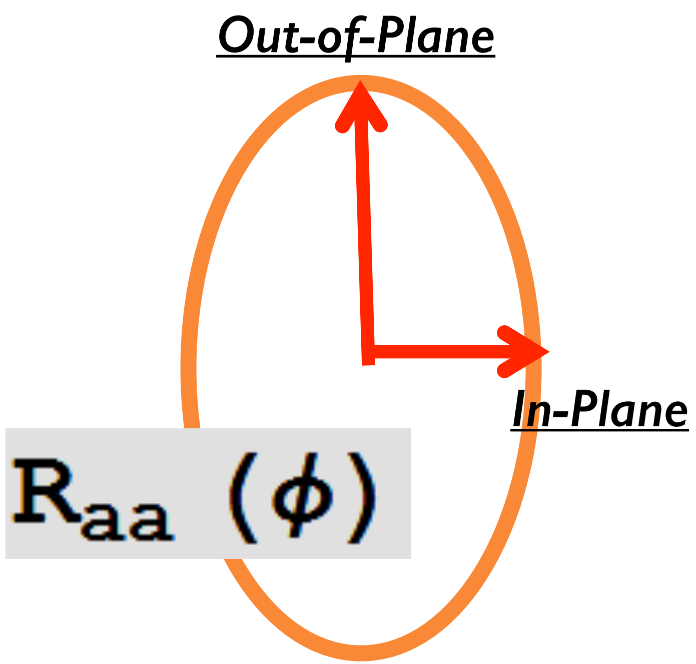
Luckily, we seem to be able to:
Geometry, (RHIC+LHC)*(Raa+V2)

The combined set of observables *(RHIC + LHC)*(Raa+V2)* are extremely powerful in pinning down nontrivial temperature dependence

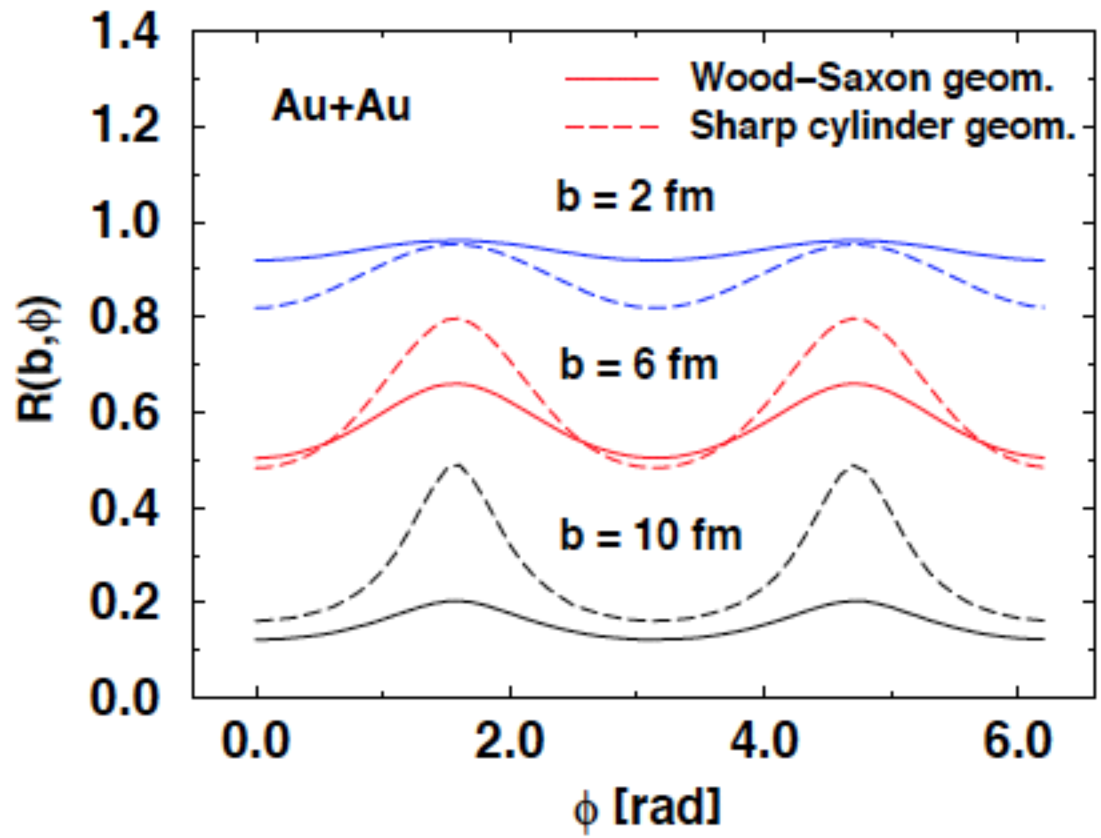
Zhang & JL, arXiv: 1208.6361,1210.1245; Betz & Gyulassy, 1305.6458, 1404.6378; Xu, Buzzatti, Gyulassy, arXiv:1402.2956

Geometric Anisotropy of Jet Quenching

Geometric tomography(~2001): Gyulassy, Vitev, Wang,...



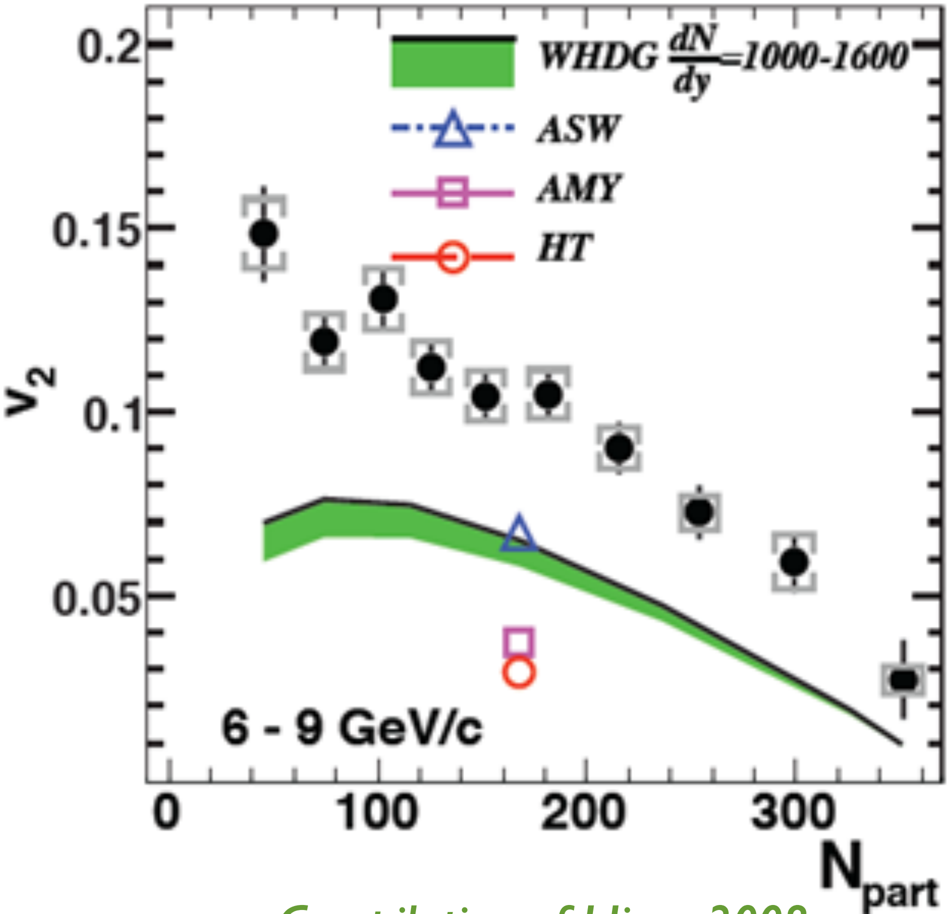
$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$



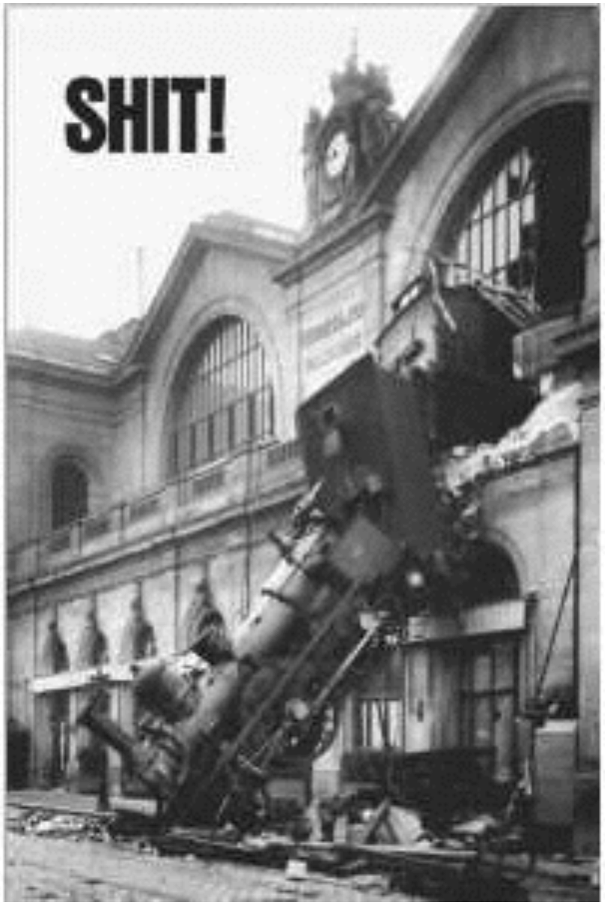
Positive v2 for high Pt hadrons — beautiful idea!

All very nice, until …

Getting Out of Control…

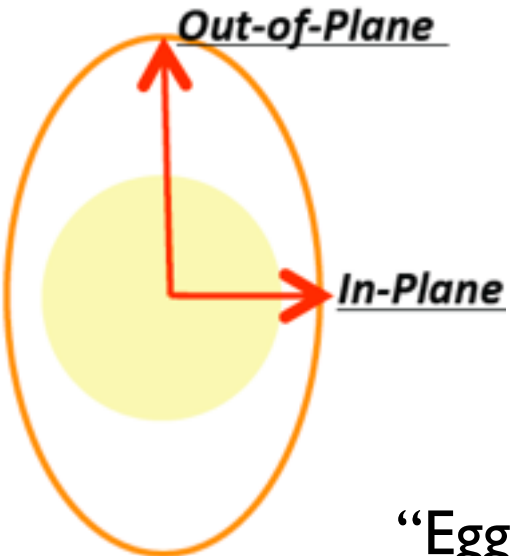


Compilation of J.Jia, ~2008



Till ~2008: clear and significant discrepancy between data / any model

Where Are Jets Quenched (More Strongly)?



Taken for granted in all previous models: "waterfall" scenario.

We realized the puzzle may concern more radical questions:

Where are jets quenched (more strongly)?

Geometry is a sensitive feature:
"Egg yolk" has one geometry, "Egg white" has another.

PRL 102, 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

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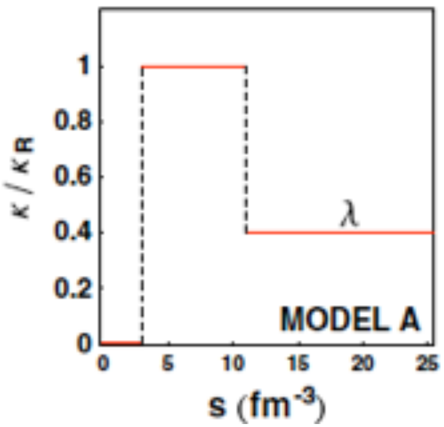
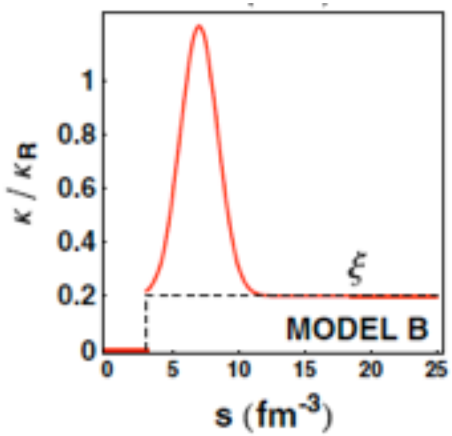
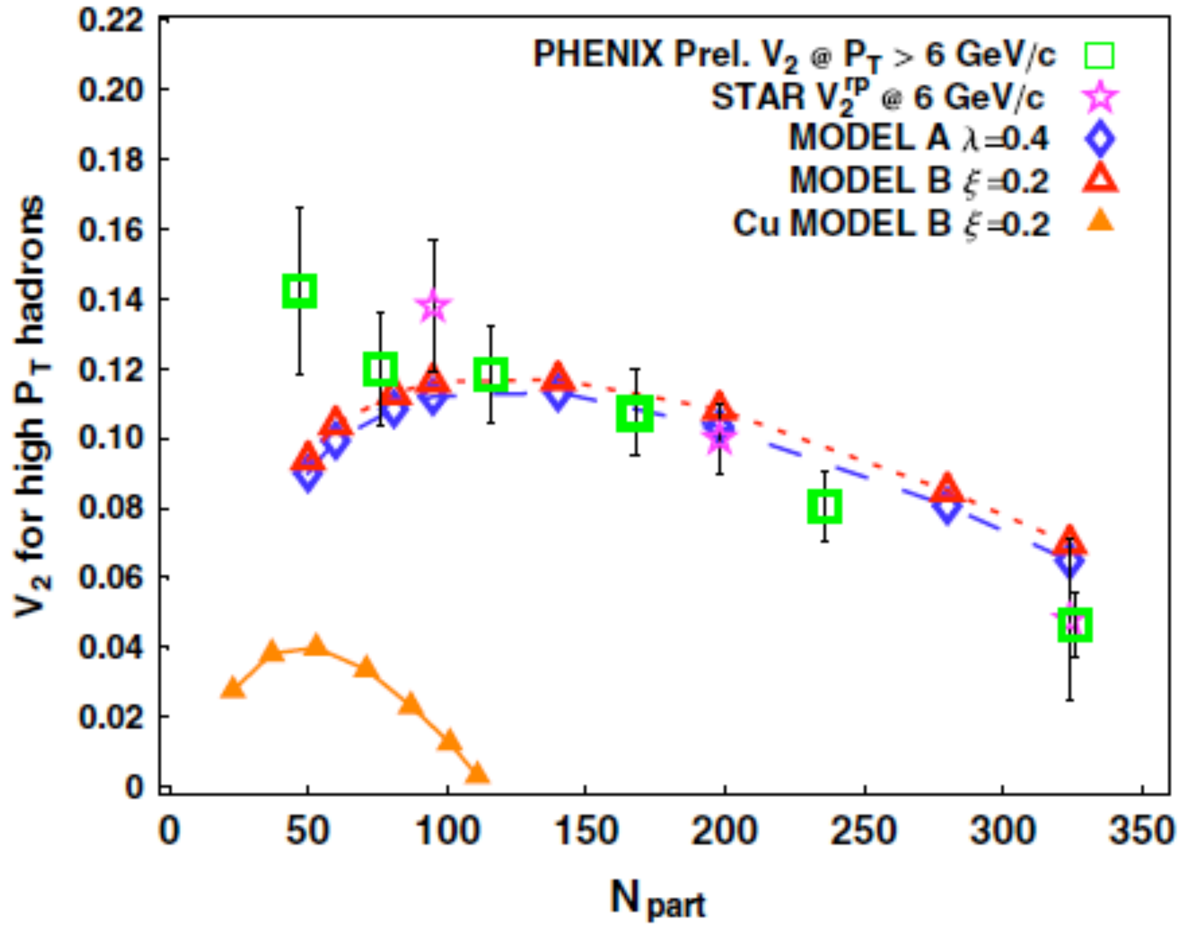
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

Near-Tc Enhancement (NTcE)





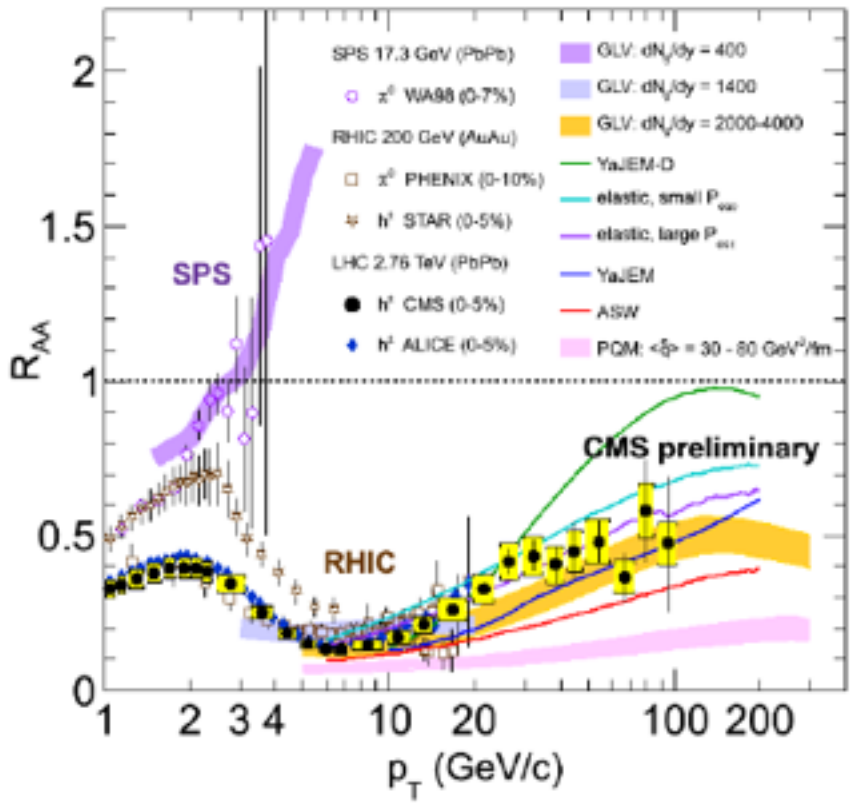


In the paper PRL(2009) we concluded:

"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

The RHIC+LHC Era

Beautiful jet quenching measurements from all collaborations

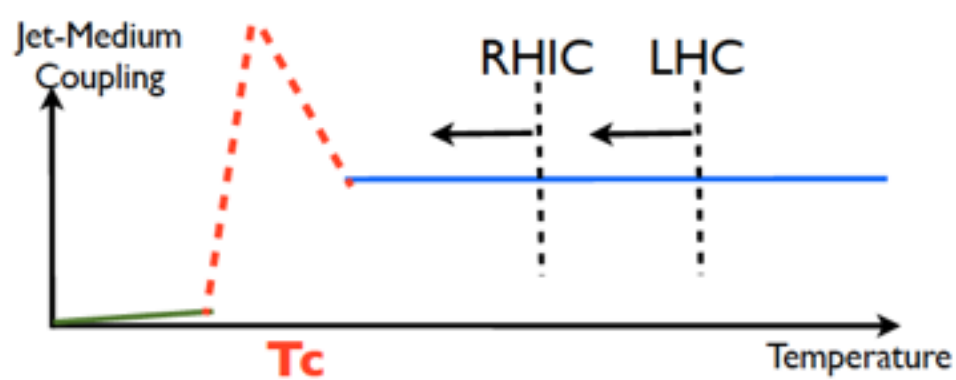


Already a clear hint of LESS OPACITY: similar R_aa, despite twice the density!

— "surprising transparency" (Horowitz & Gyulassy, QM11)

— naturally expected if the "volcano scenario" is indeed true (Liao PANIC11)

$$< \kappa >_{\rm RHIC} : < \kappa >_{\rm LHC} \approx 1 : 0.72$$

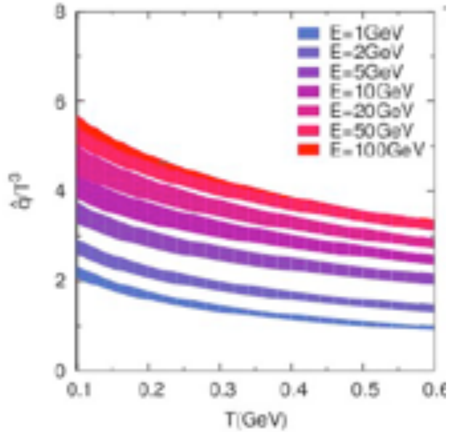


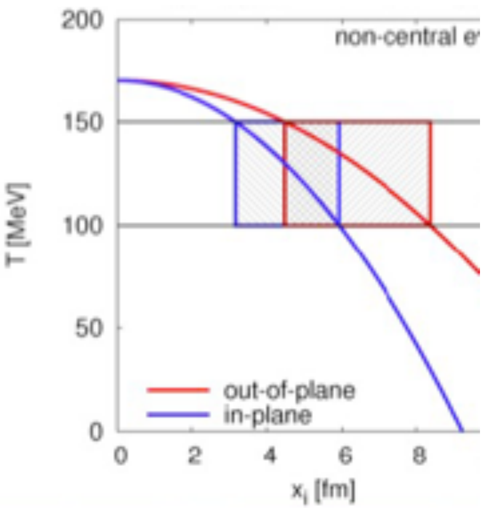
Similar conclusion from a number of analyses:

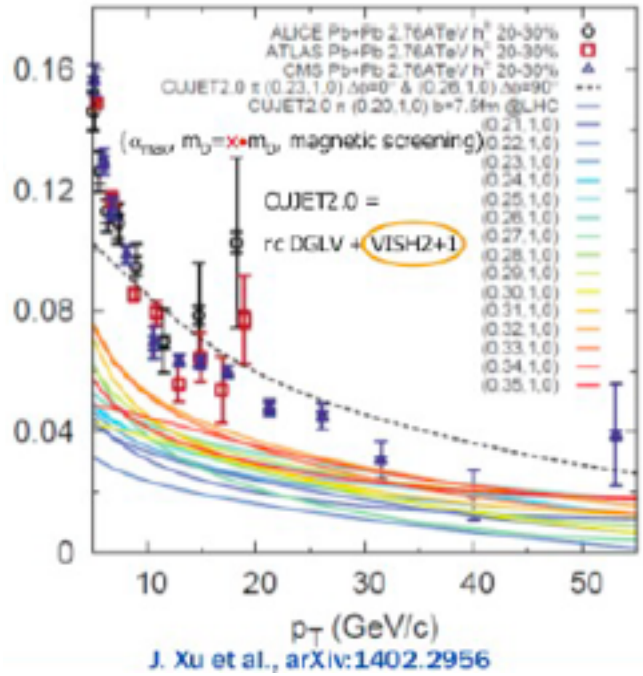
Betz & Gyulassy, 1201.0281; Buzzatti & Gyulassy, 1210.6417; Zhang & JL, arXiv: 1208.6361,1210.1245.

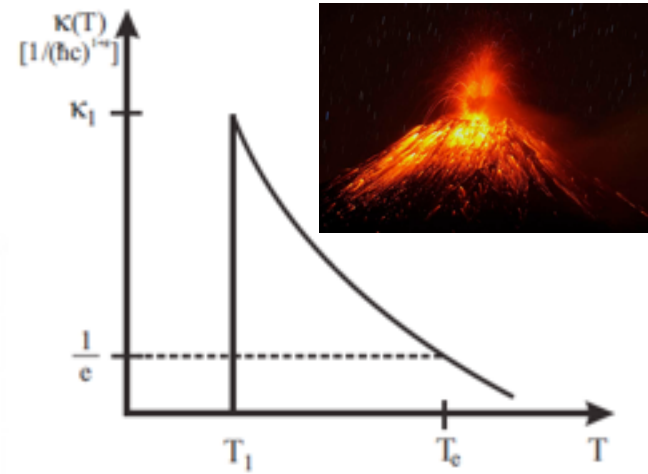
Latest Analysis from GLV-CUJET

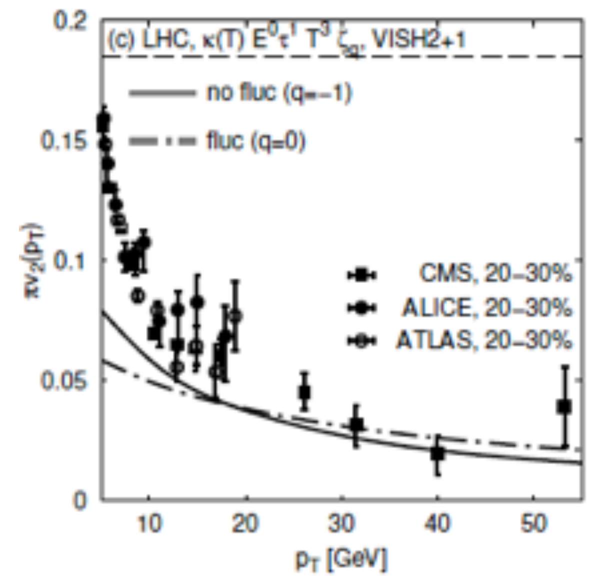
Xu, Buzzatti, Gyulassy, 1402.2956;
Betz, Gyulassy, 1404.6378









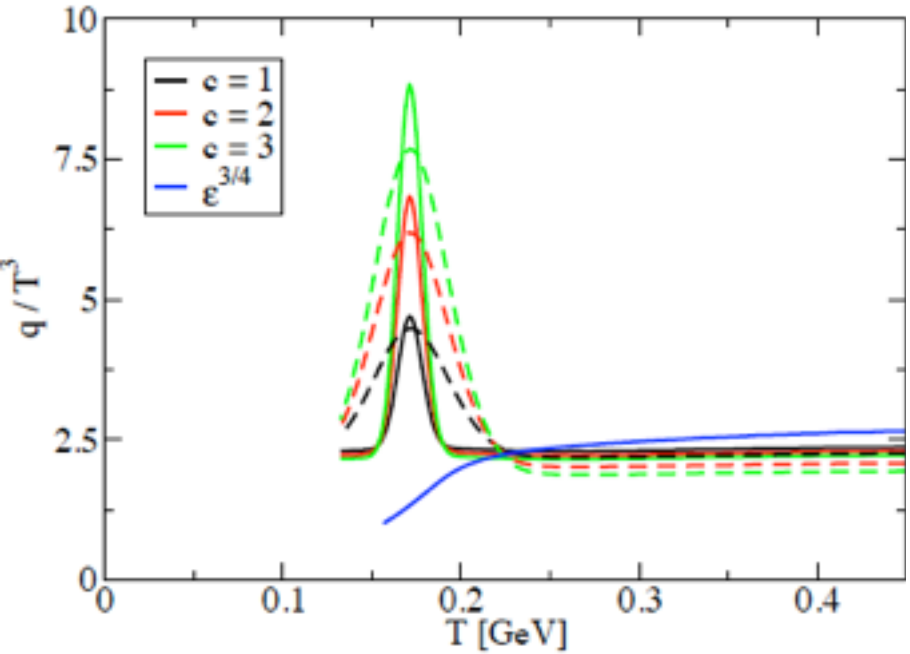


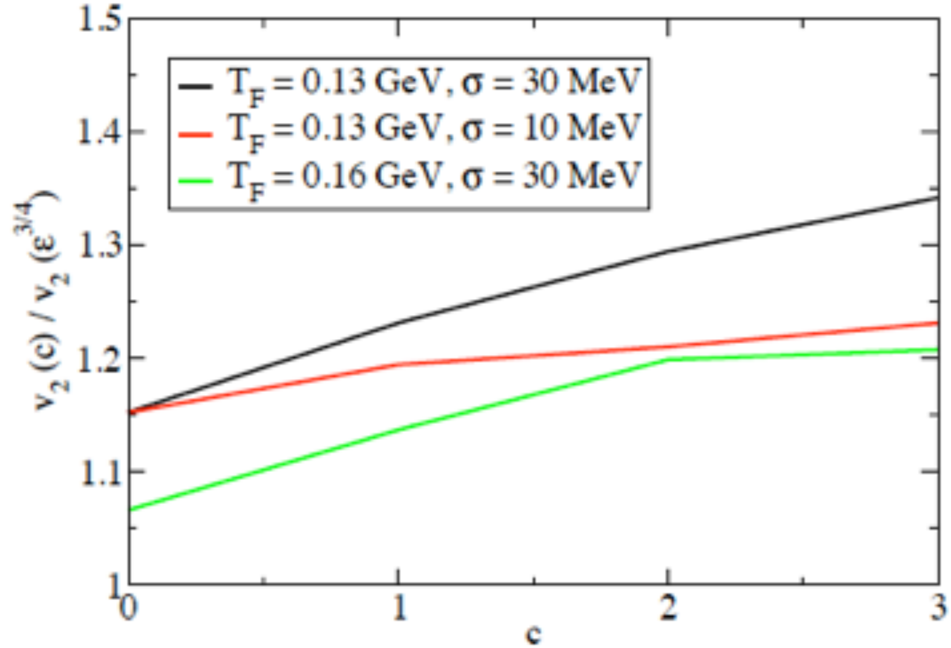
effectively:
kappa_out > kappa_in

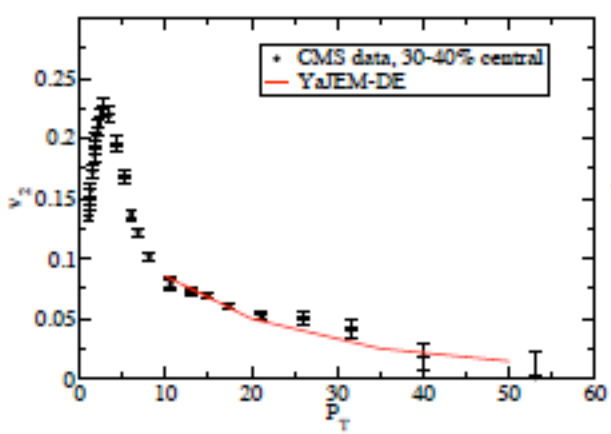
Latest Results from State-of-Art Simulations

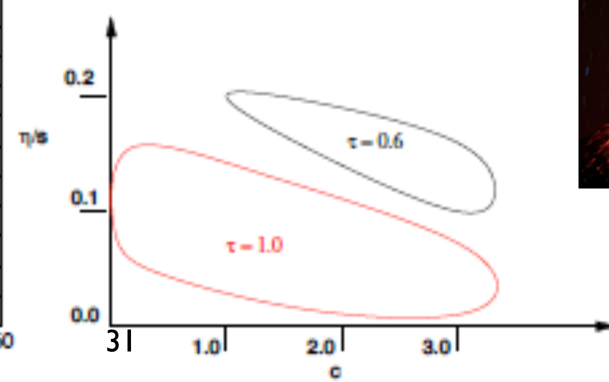
Renk, 1402.5798 & QM14

model	ASW	YDE 3d	YDE 2d
NTC/$\epsilon^{3/4}$	1.17	1.22	1.20



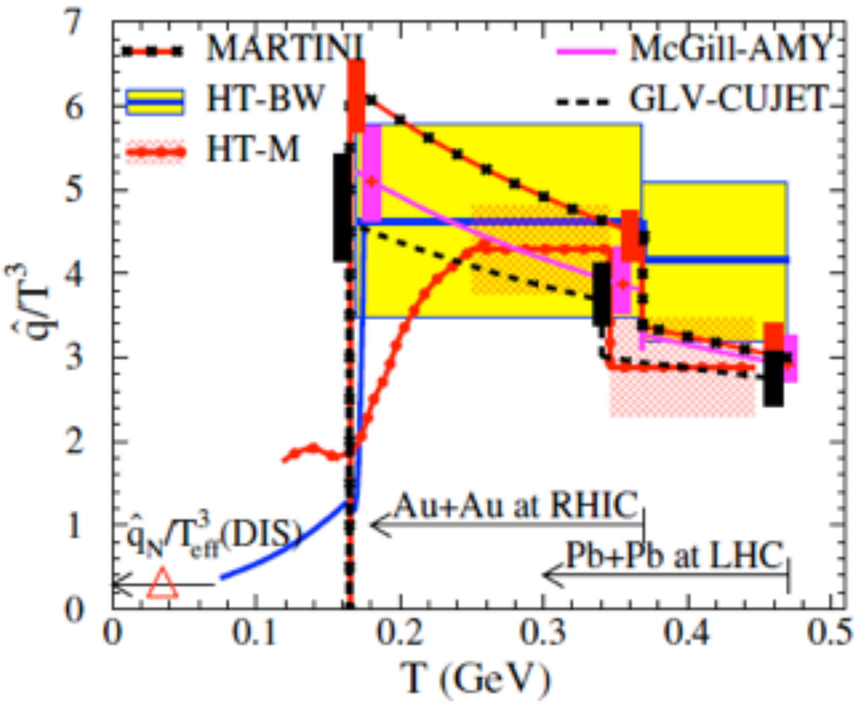


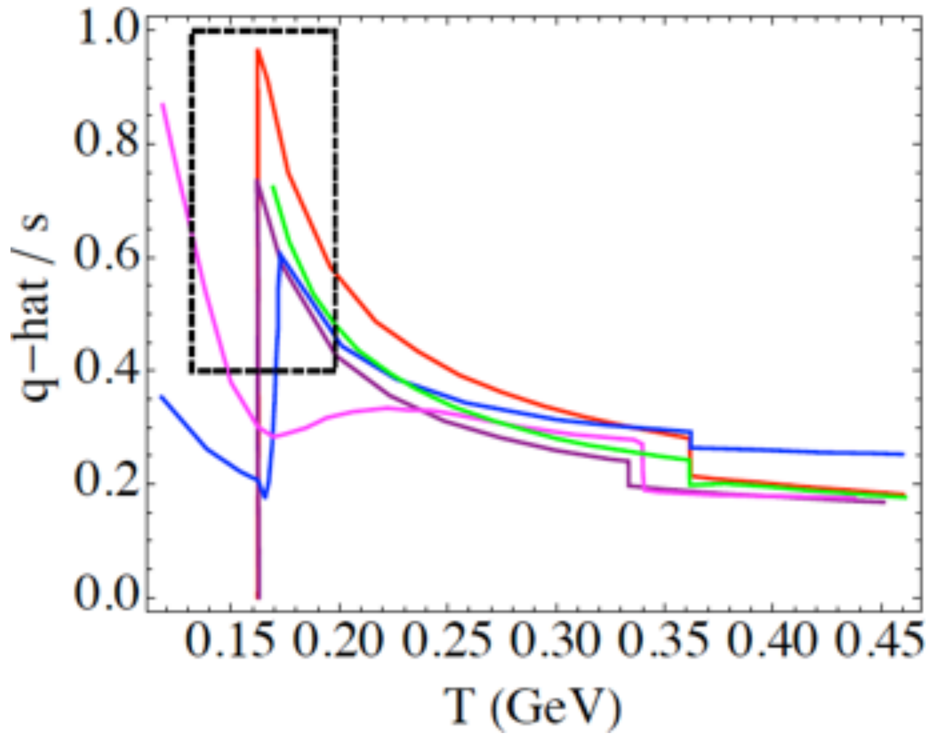


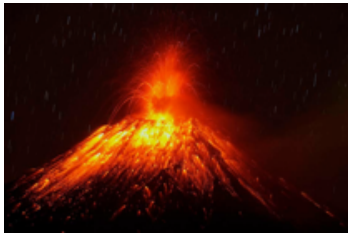


Latest Analysis from JET Collaboration

JET Collaboration, arXiv: 1312.5003



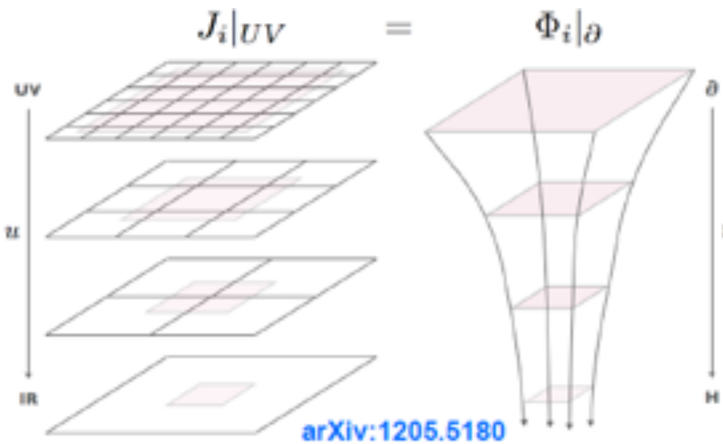




In the paper PRL(2009) we (Liao&Shuryak) concluded:

"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

Going to One More Dimension

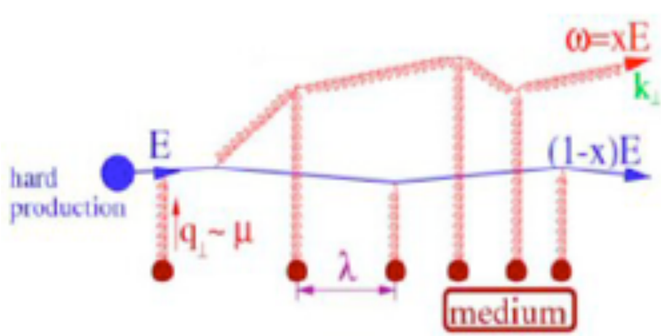


Deforming the conformal-AdS to introduce non-conformal dynamics: using graviton-dilaton system in the bulk

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R_s + 4\partial_M\Phi\partial^M\Phi - V_G^s(\Phi)\right)$$

$$\Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2/\mu_G^2)$$

$$ds_S^2 = e^{2A_s}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + dx^i dx^i\right)$$

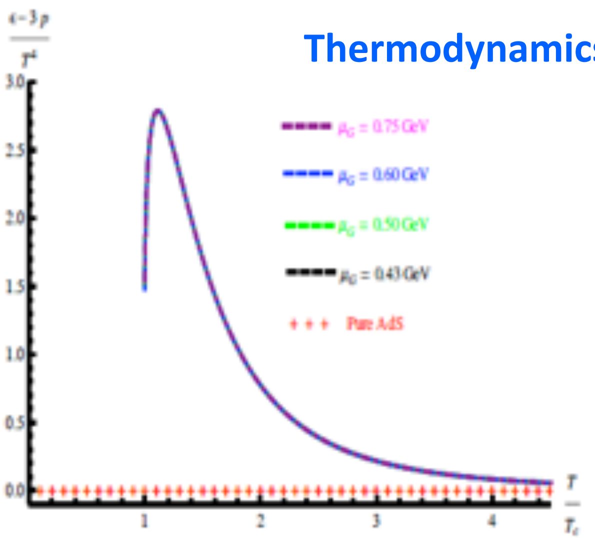


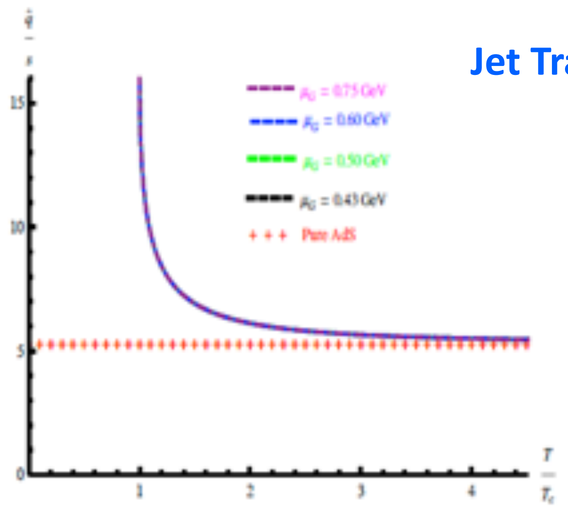
We use the Liu-Rajagopal-Wiedemann scheme to compute q-hat

$$\hat{q} = \frac{\sqrt{2}\sqrt{\lambda}}{\pi\int_0^{z_h} dz\sqrt{g_{zz}/(g_{22}^2 g_{--})}},$$

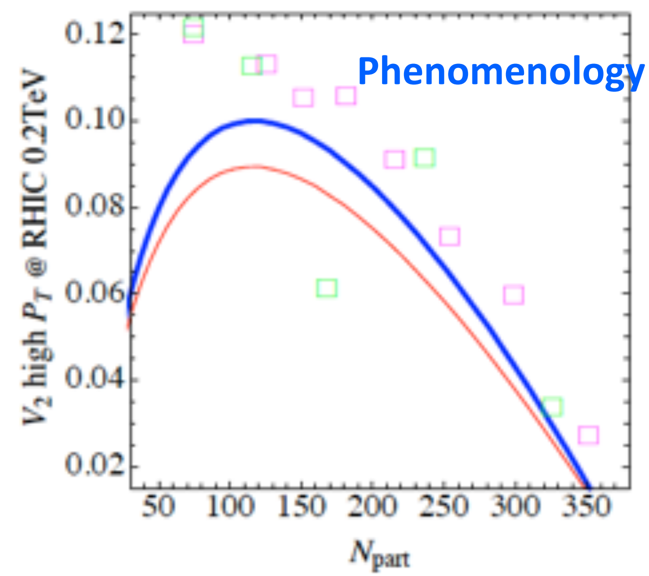
D. Li, JL, M. Huang, arXiv:1401.2035

Results from Non-Conformal Holo-QCD





Same non-conformal, non-monotonic, non-perturbative dynamics
---> shows up in trace anomaly and in jet transport parameter
---> considerably increases jet anisotropy toward data as compared with conformal case



D. Li, JL, M. Huang, arXiv:1401.2035

The semi-Quark-Gluon Monopole Plasma (sQGMP)

We Need A Microscopic Model for sQGP!

There are a number of outstanding challenges in understanding how the QGP does what it does:

** We know that there are nonperturbative dynamics and emergent degrees of freedom in sQGP — how to implement such physics?*

** Experimental & lattice data validation?*

** Perfect fluidity v.s. Jet quenching — how to reconcile the two key properties of the sQGP?*

Consistency of Perfect Fluidity and Jet Quenching in semi-Quark-Gluon Monopole Plasmas

Jiechen Xu,[1,*] Jinfeng Liao,[2,3,†] and Miklos Gyulassy[1,‡]

Xu, JL, Gyulassy, arXiv:1411.3673

A Sophisticated Simulation Framework

DGLV-CUJET framework for describing multi-parton scattering:

$$x_E \frac{dN_g^{n=1}}{dx_E} = \frac{18C_R}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau \; n(\mathbf{z})\Gamma(\mathbf{z}) \int d^2k$$
$$\times \; \alpha_s\left(\frac{\mathbf{k}^2}{x_+(1-x_+)}\right) \int d^2q \frac{\alpha_s^2(\mathbf{q}^2)}{\mu^2(\mathbf{z})} \frac{f_E^2\mu^2(\mathbf{z})}{\mathbf{q}^2(\mathbf{q}^2+f_E^2\mu^2(\mathbf{z}))}$$
$$\times \; \frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})} \left[\frac{\mathbf{k}}{\mathbf{k}^2+\chi^2(\mathbf{z})} - \frac{(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\right]$$
$$\times \; \left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}{2x_+E}\tau\right)\right] \left(\frac{x_E}{x_+}\right) \left|\frac{dx_+}{dx_E}\right| \; . \quad ($$

Original DGLV formalism has only quark/gluon scattering centers

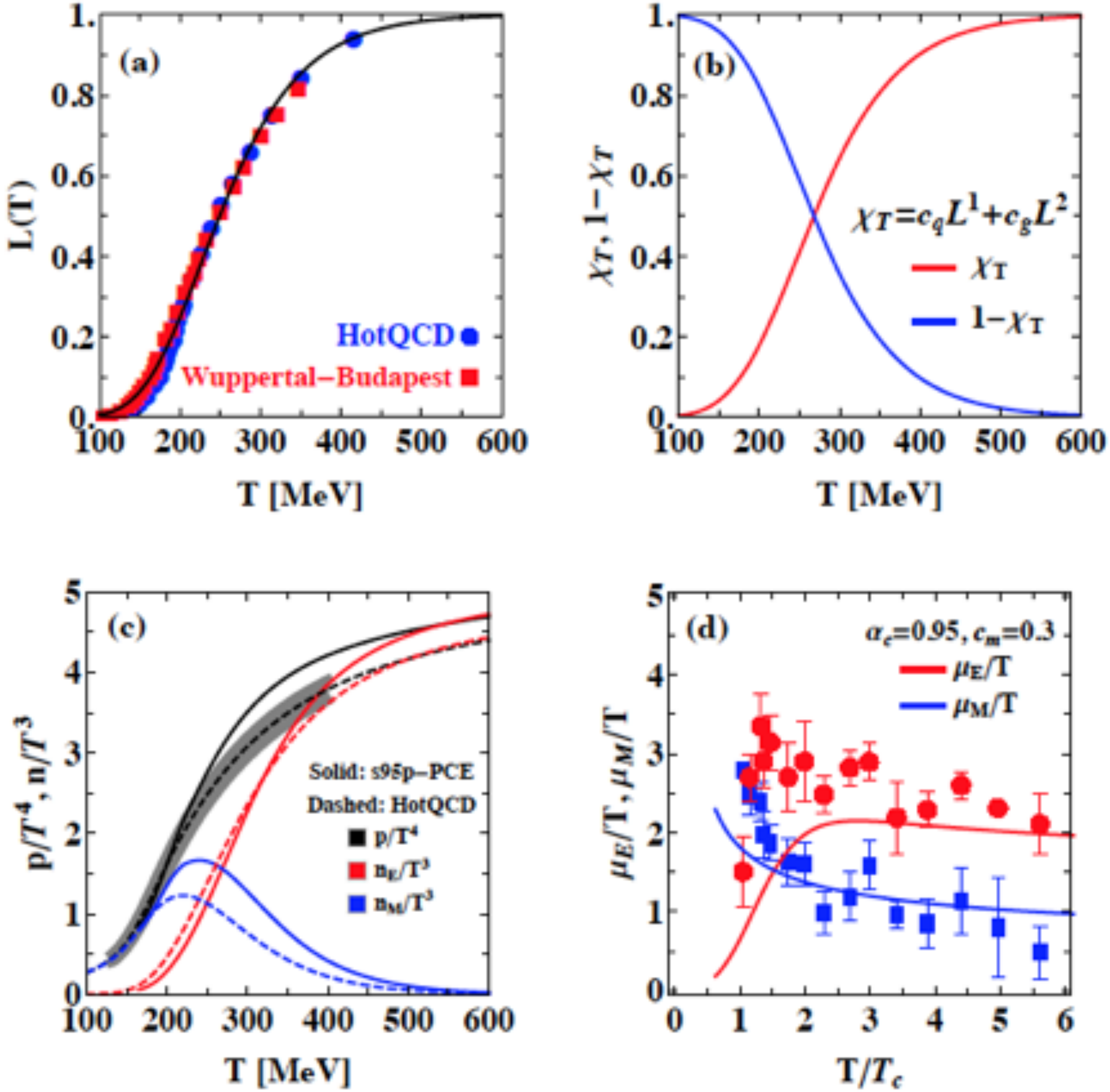
We now include both color-electric and color-magnetic scattering centers.

$$x\frac{dN}{dx} \propto \ldots \int_{q^2} \left[\frac{n\,\alpha_s^2(q^2)\,f_E^2}{q^2(q^2+f_E^2\mu^2)}\right] \ldots \;\longrightarrow\; \left[\frac{n_e\,(\alpha_s(q^2)\alpha_s(q^2))\,f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m\,(\alpha^e(q^2)\alpha^m(q^2))\,f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

Our goal is to implement the nonperturbative NEAR-Tc Physics
—> CUJET3.0

Xu, JL, Gyulassy, arXiv:1411.3673

The Making of sQGP



** Electric density:*
L-loop suppression

$$\chi_T = c_q\, L + c_g\, L^2$$

** Magnetic density:*
constrained by total pressure

$$(1 - \chi_T)$$

** Running coupling:*
L-loop suppression

$$\alpha_s(Q^2) = \alpha_c / \left[1 + \frac{9\alpha_c}{4\pi}\mathrm{Log}\left(\frac{Q^2}{T_c^2}\right)\right]$$

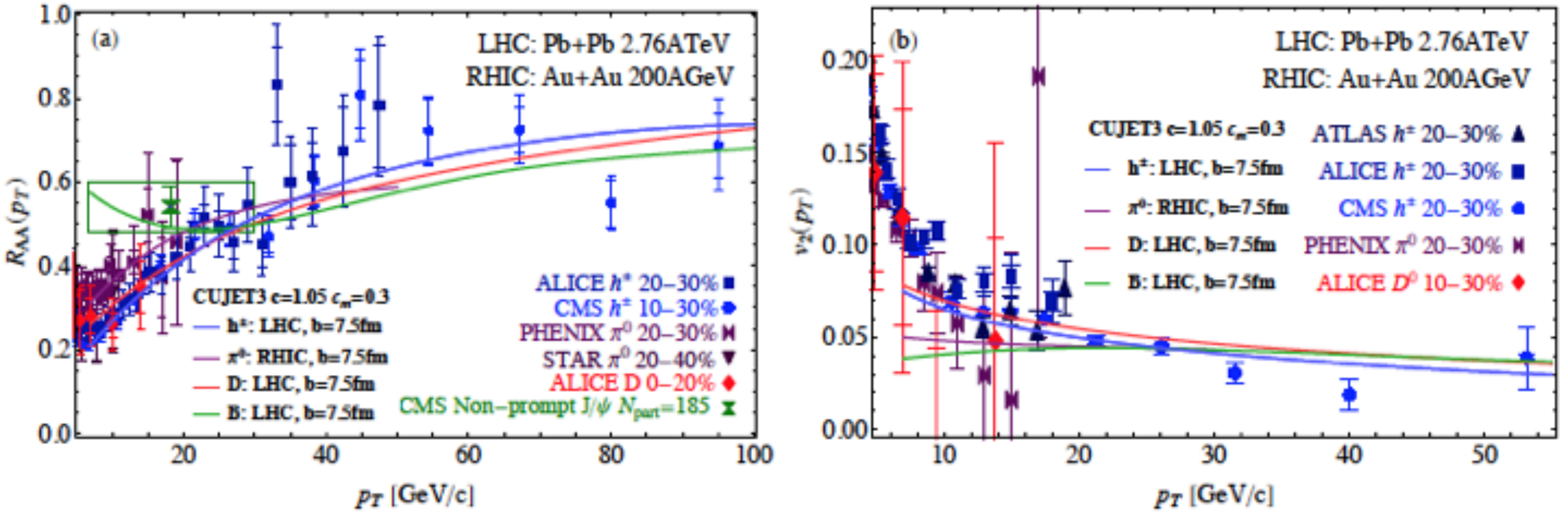
** Screening:*

$$f_E(T) = \sqrt{\chi_T} \quad , \quad f_M(T) = c_m\, g$$

The model implementations of electric and magnetic components are **well constrained by available lattice data.**

Xu, JL, Gyulassy, arXiv:1411.3673

CUJET3.0 Explains (RHIC+LHC)*(Raa+V2)!



The SEVEN set of single hadron observables

[(RHIC+LHC) * (RAA+V2) * (pion)]

+ [(LHC) * (RAA+V2) * (D)]

+ [(LHC) * (RAA) * (B)],

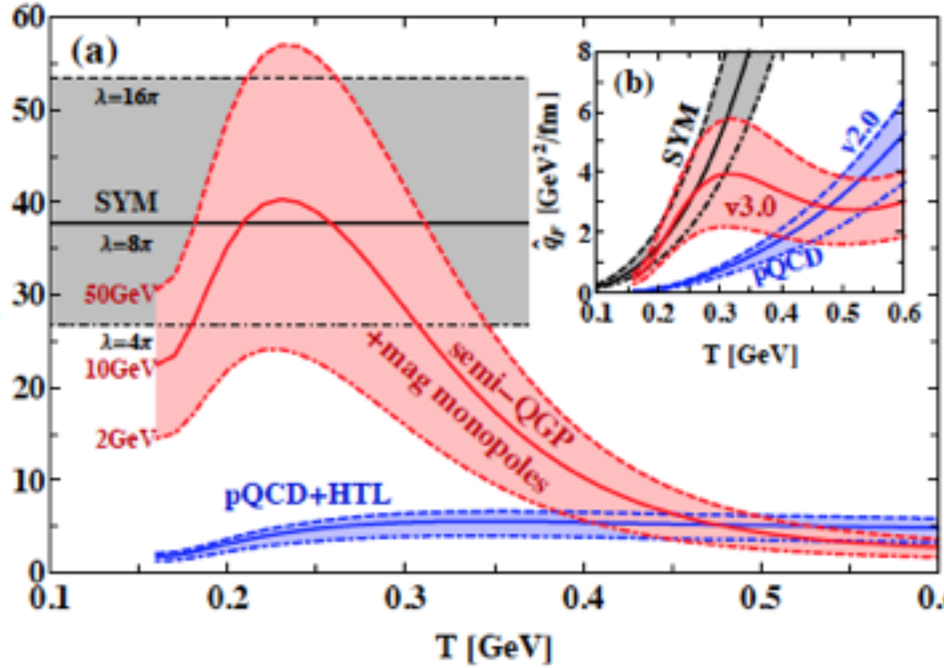
are nicely explained by CUJET3.0 framework

(with essentially ONE model parameter)

that implements the nonperturbative near-Tc physics!

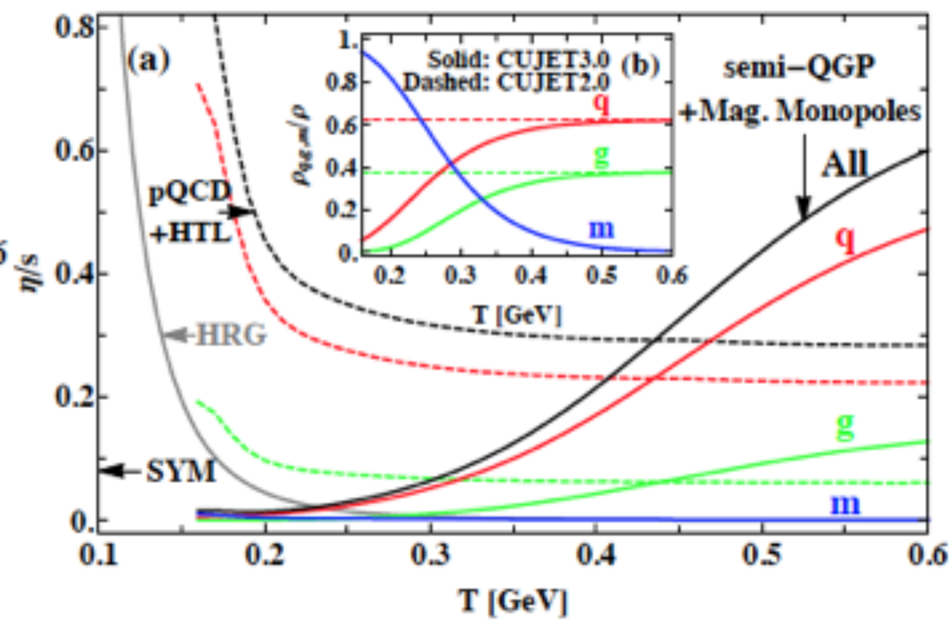
Xu, JL, Gyulassy, arXiv:1411.3673

Near-Tc Matter Properties are Special!



Jet transport coefficient q-hat/T^3 computed from CUJET3.0 shows a prominent peak near Tc!

Shear viscosity, eta/s, computed from CUJET3.0 shows a clear minimum near Tc and rapid increase to high T!



CONSISTENCY of Perfect Fluidity & Jet Quenching in the semi-quark-gluon monopole plasma (sQGMP)!

Xu, JL, Gyulassy, arXiv:1411.3673

(An Old) Summary

- Emergent D.o.Fs are important at strong coupling: magnetic monopoles
- Monopoles dominate the matter structure for near Tc plasma (at RHIC)
- **Expect rapid change of matter structure away from the near Tc regime** (transport properties, jet quenching, …)
- Hopefully we will know soon (with LHC top energy results):
  what kind of matter is the sQGP &
  how does it evolve from RHIC to LHC?

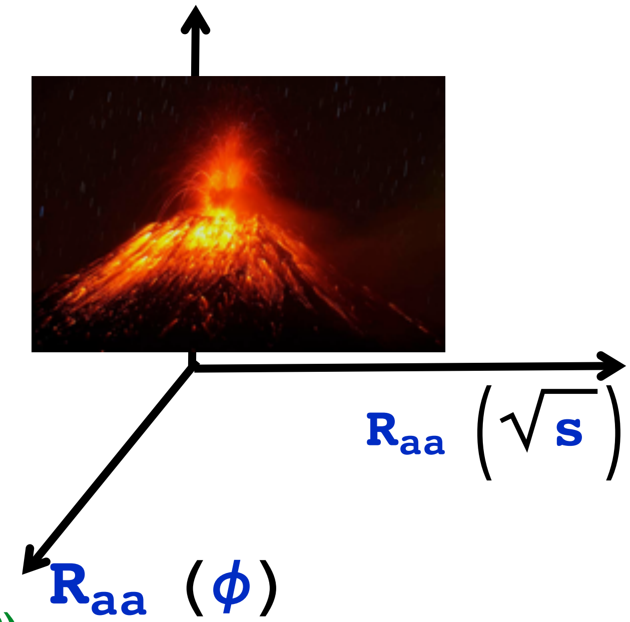
WE NOW KNOW THE ANSWER TO THIS!

Summary

* An exciting time: ***quantitatively*** determine and understand the temperature dependence of QGP transport properties.

* Geometry + Evolution from RHIC to LHC:
strong evidences for Near-Nc Dynamics
— the most perfect fluid and most opaque plasma, consistently!
— similar implications for the in-medium dynamics of open heavy flavor and quarkonia as well!

* RHIC + LHC together provide unique opportunities for probing the transition zone between the confined world and the asymptotically free matter.



* Significant progress in understanding the microscopic working of sQGP:
semi-quark-gluon monopole plasma (sQGMP).