APS April Meeting April 13, 2015
Session U3: Invited Session: DNP Prize Session

Miklos Gyulassy   (Columbia University)

Jet Tomography of Quark Gluon Plasmas in High Energy Nuclear Collisions

(Using hard Jets to probe soft phases of Bulk QCD Matter)

1. Introduction with Acknowledgements

2. My Initial Conditions and my path from Bevalac to LHC via RHIC

3. Jet Quenching and Jet Tomography Theory and Phenomenology

   Predictions & Puzzles & Solutions

5. Current Open Questions

To celebrate the possibility that humankind can probe, through RHIC, the origin of the universe and the complexity of the vacuum, Li Keran dedicated

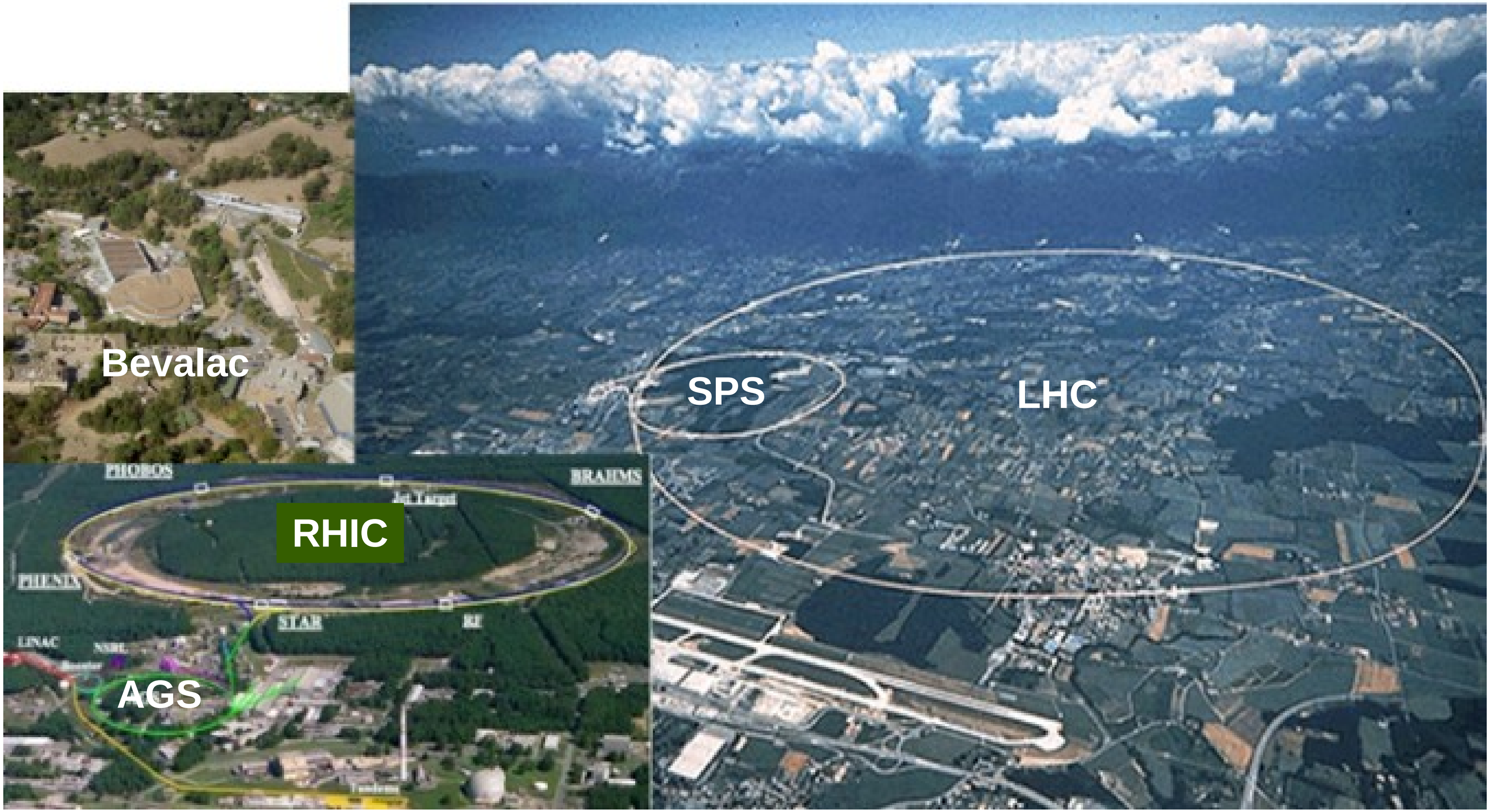
(T.D.Lee 1989)

Nuclei As Heavy As Bulls
Through Collision Generate New States of Matter

40, 000 Man Years of Exploration and Discovery of New Extreme Forms of QCD Matter

Via p+p to p· $\sqrt{s} = 1\ \mathbf{AGeV} - 5\ \mathbf{ATeV}$

40 years of A+A accelerator and detector development from 1974 - today



Mine is a story of strong long range collective interactions between me

and

~ 100 Theorists ITP/Goethe, LBL, Columbia, BNL, Wigner/MTA, ...

and

~1000 Experimentalist at GSI Bevalac AGS SPS RHIC and LHC

Spanning 40 years in time

> Science is the knowledge of many,
> orderly and methodically digested and arranged,
> so as to become attainable by one.
> (J.F.W. Herschel)

Some of my many collaborators to whom I owe my deepest thanks

Xin-Nian Wang since 1989 my most esteemed collaborator and friend

Somehow we became coauthors in 1990 with

John Harris and **38** experimentalists including **Howard Weiman**,
T. Hallman, P. Jacobs, **Art Poszkanzer**, R. Stock, J.Symons, ….

On an *Experimental* 1990 LBL-29488 TPC proposal (later called STAR)

“Concept for an experiment on particle and jet production at mid-rapidity “

“to study correlations between global observables on an event by event basis and the use of hard scattering of partons as a probes of the properties of high density nuclear matte r”

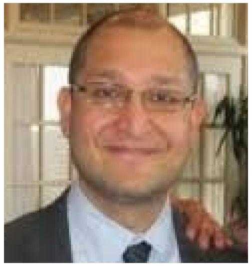
Xin-Nian and I wrote during 1990 the first of our 33 papers on
“Jets in relativistic heavy ion collisions”

It was my great fortune and privilege to have work so many smart colleagues , postdoc and PhD students around the world on high energy nuclear collisions

NSD/LBNL , Columbia Uni, Goethe ITP Frankfurt, RBRC/BNL, CERN, INS Tokyo, INT/U.Wash, and the MTA Wigner Research Center, Budapest.

My elite Columbia Univ PhD Students with whom I enjoyed working with since 1992 on

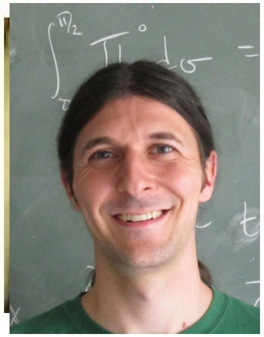




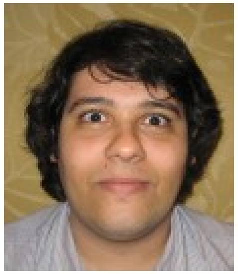
Jet Tomography and AdS Holography

I.Vitev, M.Djordjevic, A. Adil.

W.Horowitz, S. Wicks, A. Buzzatti, A. Ficnar, B. Betz, J. Noronha, J.Xu





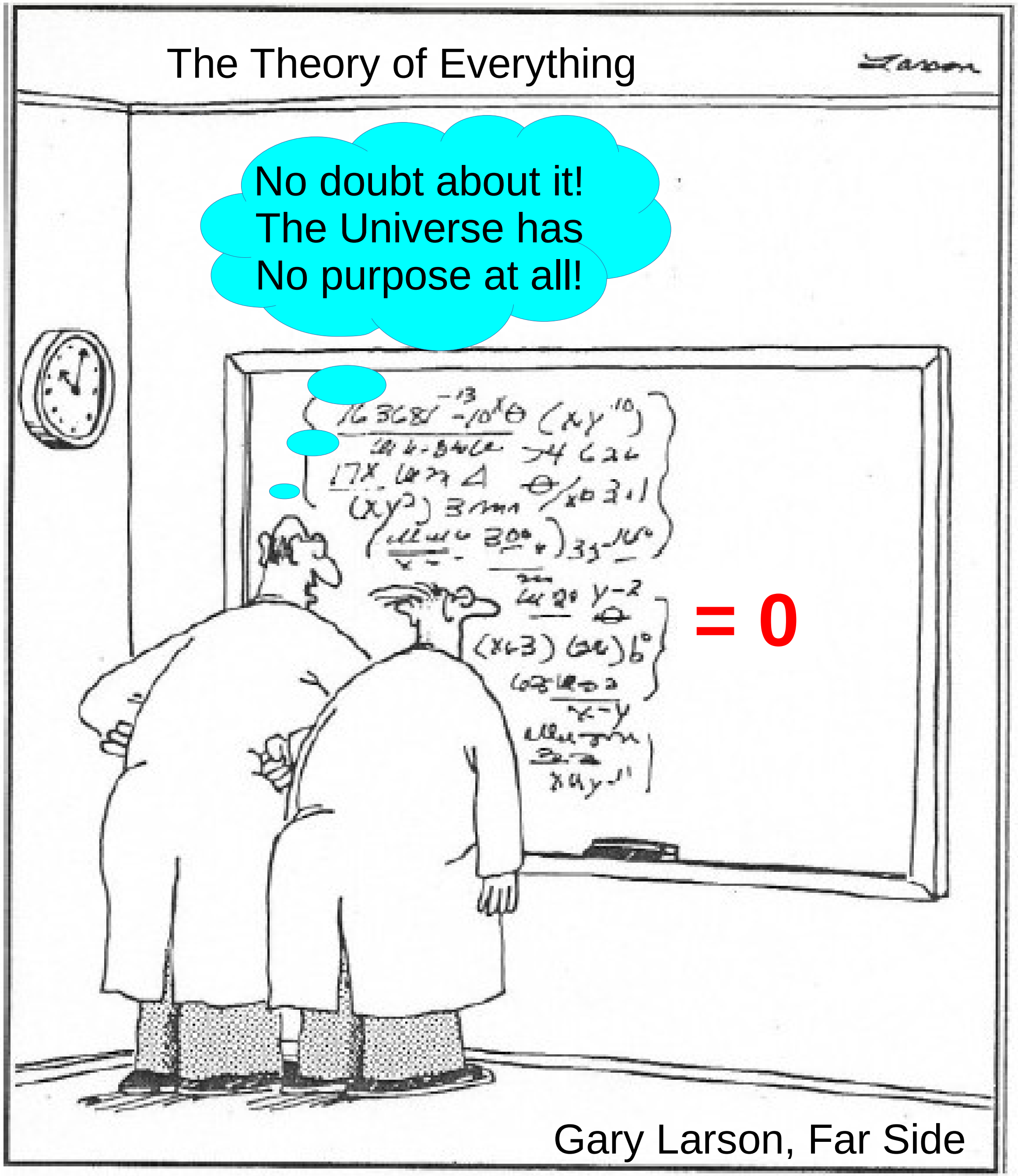




A+A Transport and Hydrodynamics

Z. Lin B. Zhang D.Molnar S.Vance



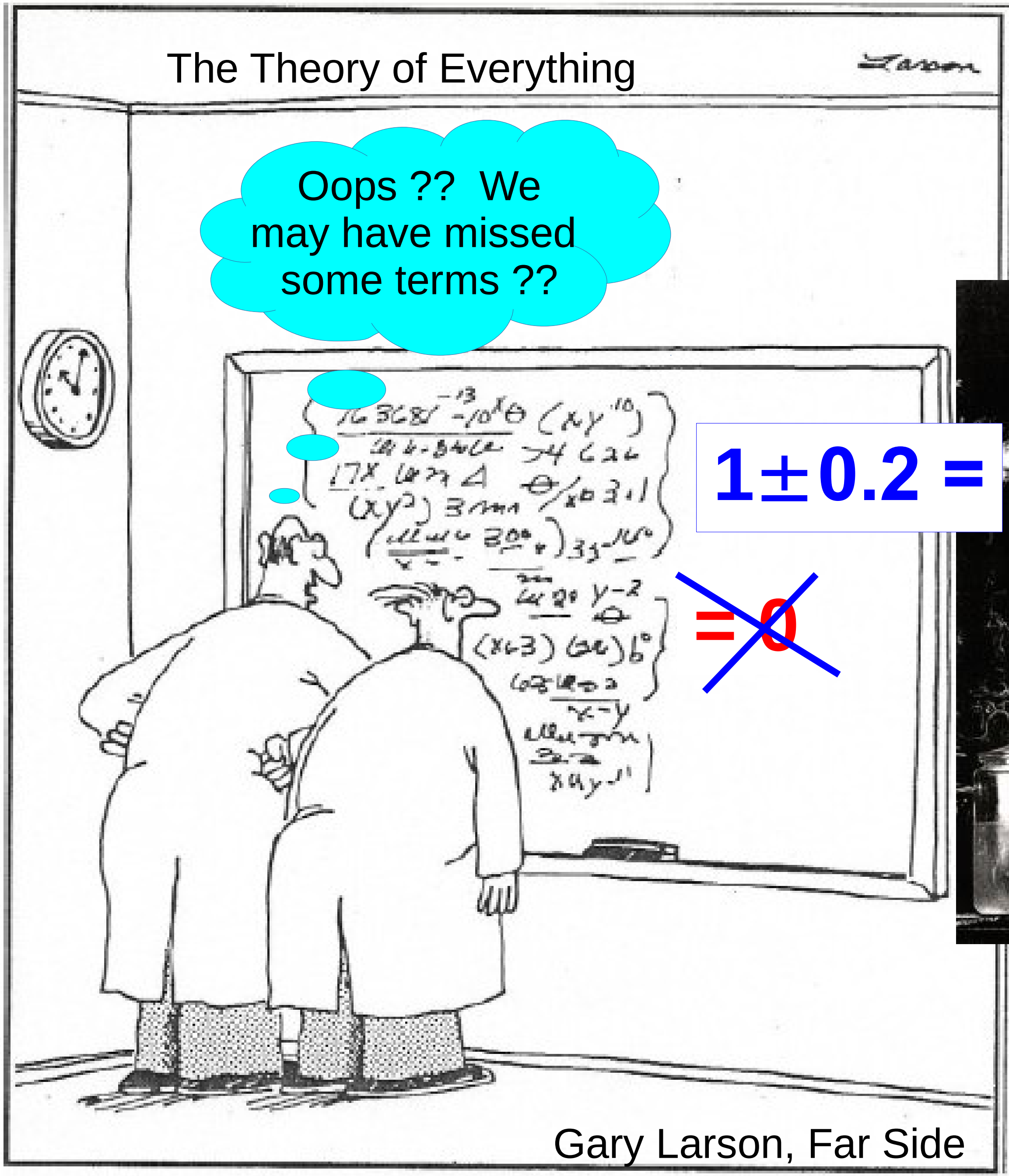

Theorist at work in their Ivory Towers and that "Ah Ha" moment



"No doubt about it, Ellington—we've mathematically expressed the purpose of the universe. Gad, how I love the thrill of scientific discovery!"

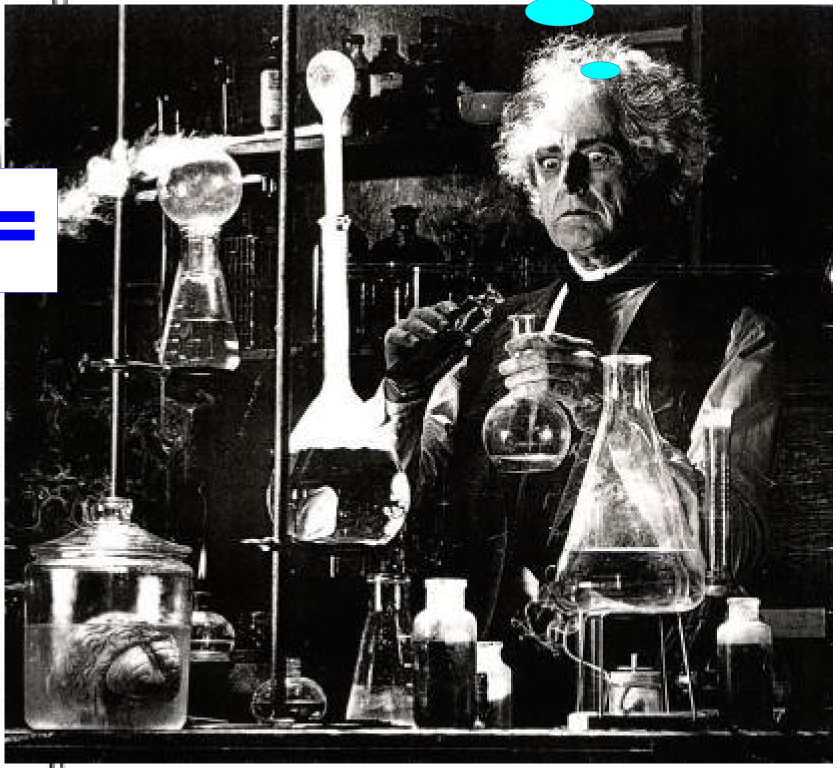
Theorist at work in their Ivory Towers: the “Oops” moment

The Universe apparently ***does have*** a Purpose at 5 σ !



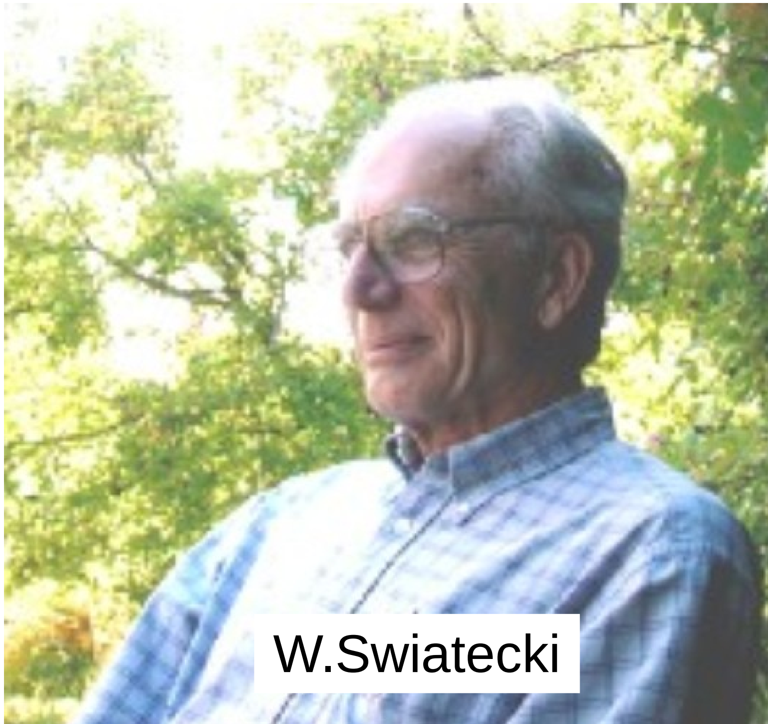
$1 \pm 0.2 =$

~~= 0~~



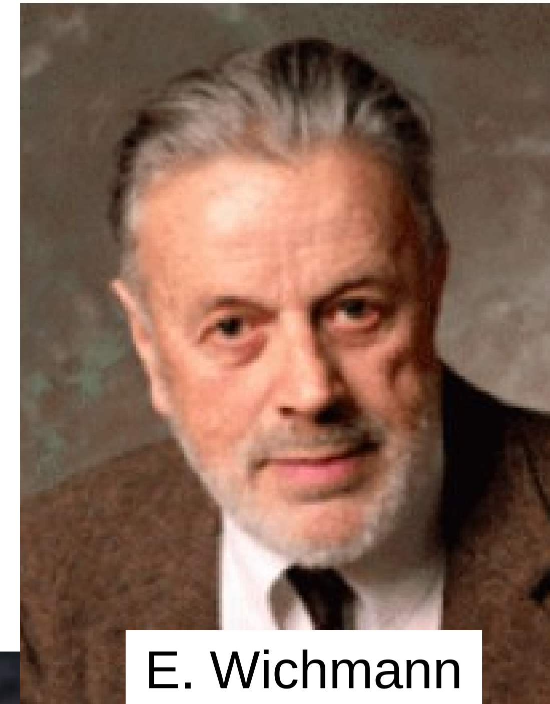
Experimentalists Always have the Last Word In Physics

I am here today, as a representative of the heavy ion theory community, who enjoy being forced by experiment to look for missing terms in their equations

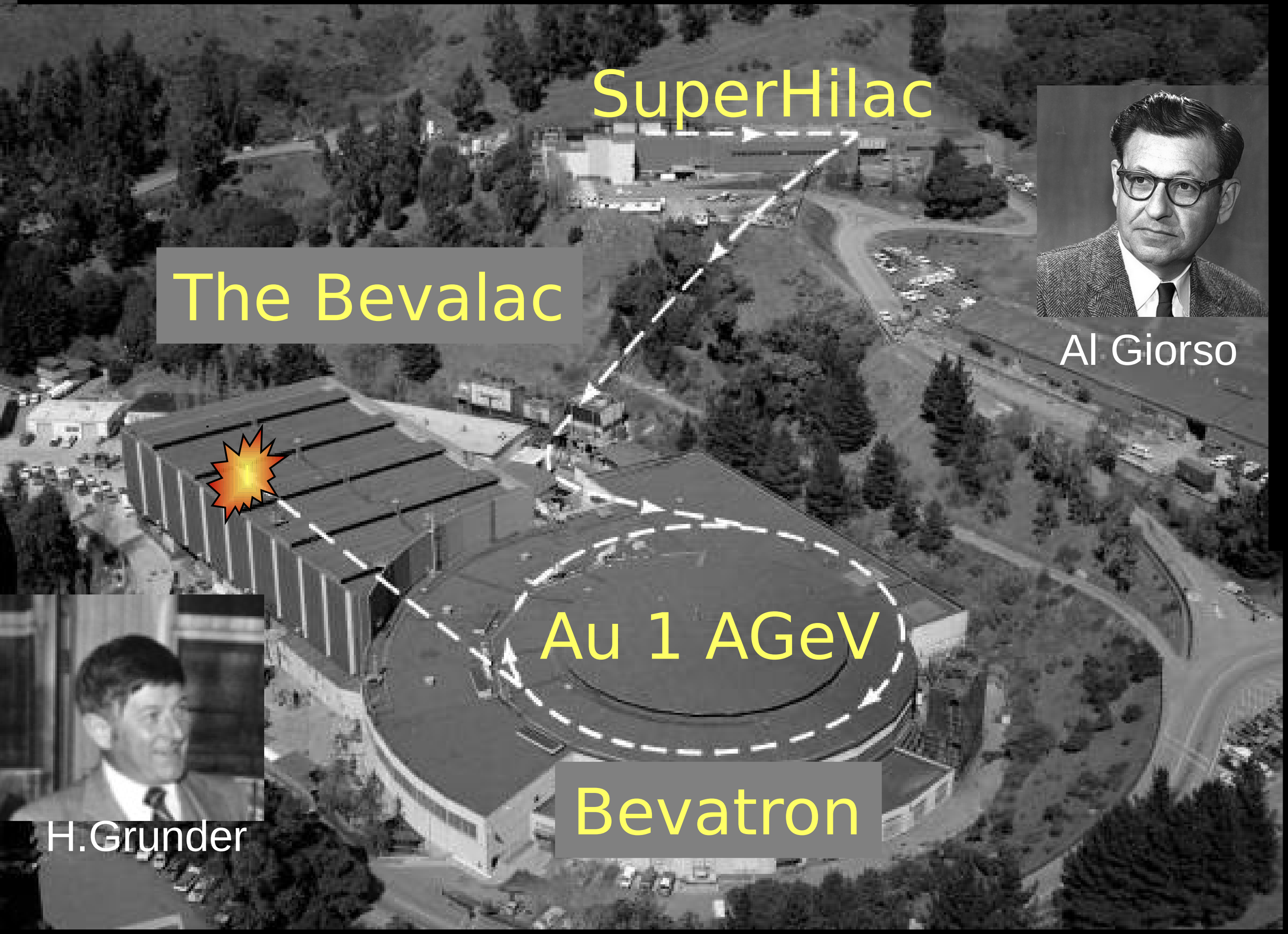


My Initial Conditions:
1974 UC Berkeley

High Field QED
Z $\alpha > 1$ via
Heavy ion collisions



Lawrence Lab 1974 (my right-place/right-time luck)



Nuclear Chemistry Alchemy:
Ne +Pb -> Au + X

&

The birth of Reverse Alchemy
Au+Au -> ??

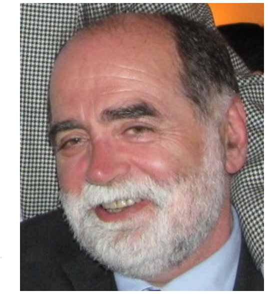
- T.D. Lee, C. Wick, “Abnormal Nuclear States and Vacuum Excitations” (74)
- W. Greiner, H.Stöcker “Nuclear Shock Waves in Heavy Ion Collisions”(74)
- J.C. Collins, M.F. Perry “Superdense Matter… Asymptotically Free Quarks?” (75)
- M. Gyulassy, W. Greiner “Pion Condensation in Heavy Ion Collisions” (76)
- E. Shuryak “Quark-Gluon Plasma and Hadronic Production of Leptons (78)
- J.D.Bjorken, L.McLerran “Explosive Quark Matter and the Centauro Event (79)
- M. Gyulassy, et al “Pion Interferometry of Nuclear Collisions” (79)

Pioneering works that strongly influenced mine

PHYSICAL REVIEW D VOLUME 20, NUMBER 9 1 NOVEMBER 1979

Explosive quark matter and the "Centauro" event

J. D. Bjorken and L. D. McLerran



We study the hypothesis that the "Centauro" event found by the Brazil-Japan cosmic-ray emulsion collaboration is initiated by the explosion of a metastable glob of highly compressed hadronic matter present

A cosmic ray event with "too few " pi0

$$\frac{N(\pi^0)}{N(\pi(all))} \ll \frac{1}{3} \pm \frac{1}{\sqrt{N}}$$

PHYSICAL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

Central collisions between heavy nuclei at extremely high energies: The fragmentation region

R. Anishetty*
Physics Department, University of Washington, Seattle, Washington 98195

P. Koehler and L. McLerran†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 11 August 1980)

We discuss central collisions between heavy nuclei of equal baryon number at extremely high energies. We make a crude estimation of the energy deposited in the fragmentation regions of the nuclei. We argue that the fragmentation-region fragments thermalize, and two hot fireballs are formed. These fireballs would have rapidities close to the rapidities of the original nuclei. We discuss the possible formation of hot, dense quark plasmas in the fireballs.

Pioneering works that strongly influenced mine

Volume 78B, number 1 PHYSICS LETTERS 11 Spetember 1797

QUARK–GLUON PLASMA AND HADRONIC PRODUCTIO
OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

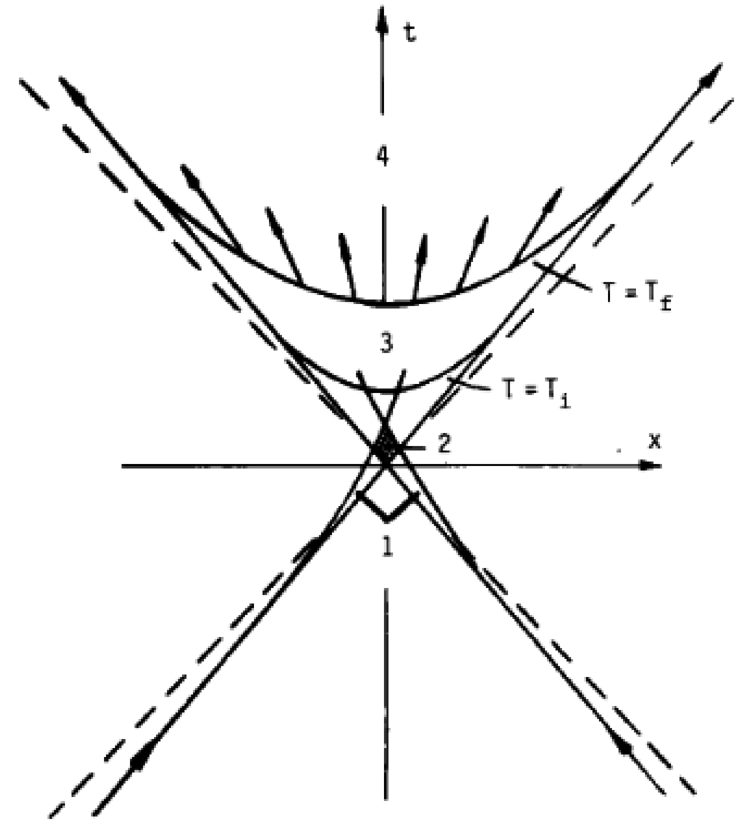


Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.

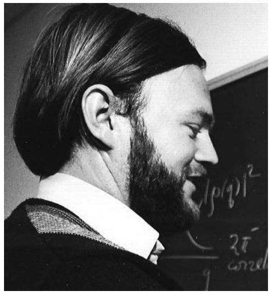
E.V. Suryak, "QCD and the Theory of Superdense Matter", Phys.Rep 61C (1980)

.

J.I. Kapusta, QCD at High Temperature, Nucl.Phys. B148 (1979) 461-498

D.J.Gross, R.D.Pisarski, L.G.Yaffe,``QCD and Instantons at Finite Temperature,'' Rev.Mod.Phys.53 (1981)

PHYSICAL REVIEW C VOLUME 20, NUMBER 6 DECEMBER 1979



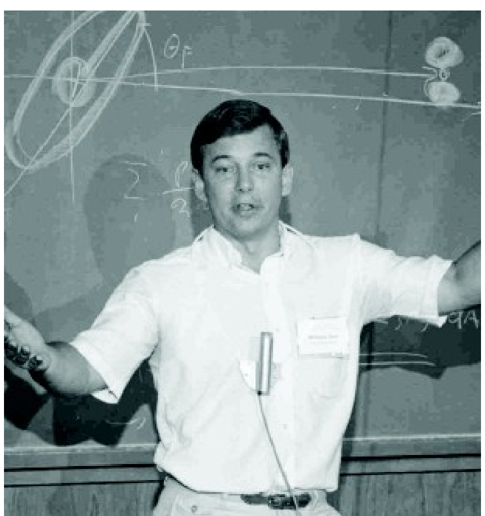
Pion interferometry of nuclear collisions. I. Theory

M. Gyulassy, S. K. Kauffmann, and Lance W. Wilson
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 3 May 1979)

The topic of pion interferometry (identical pion correlations) is analyzed in detail in the context of relativistic nuclear collisions. Through an exactly solvable field theoretic model specified by an ensemble of classical pion source currents, $J_i(x)$, we calculate the $\pi^-\pi^-$ correlation function $R(\vec{k}_1,\vec{k}_2)$ for chaotic, coherent, and partially coherent pion fields. We analyze how R can be used to determine the degree of coherence of the produced pion field as well as the geometric structure of the source of the chaotic field

(2 photon Hanbury Brown Twiss vs 2 pion GGLP intensity interferometry)

Pion Interferometry For Relativistic Heavy Ion Collisions.
W.A. Zajc, J.A. Bistirlich, R. Bossingham, H.R. Bowman, K.M. Crowe, K.A. Frankel, O. Hashimoto, W.John Mcdonald, D. Murphy, J.O. Rasmussen (LBL, Berkeley) et al..
Hakone 1980, High-energy Nuclear Int and Properties Of Dense Nuclear Matter, Vol. 1, 393-410



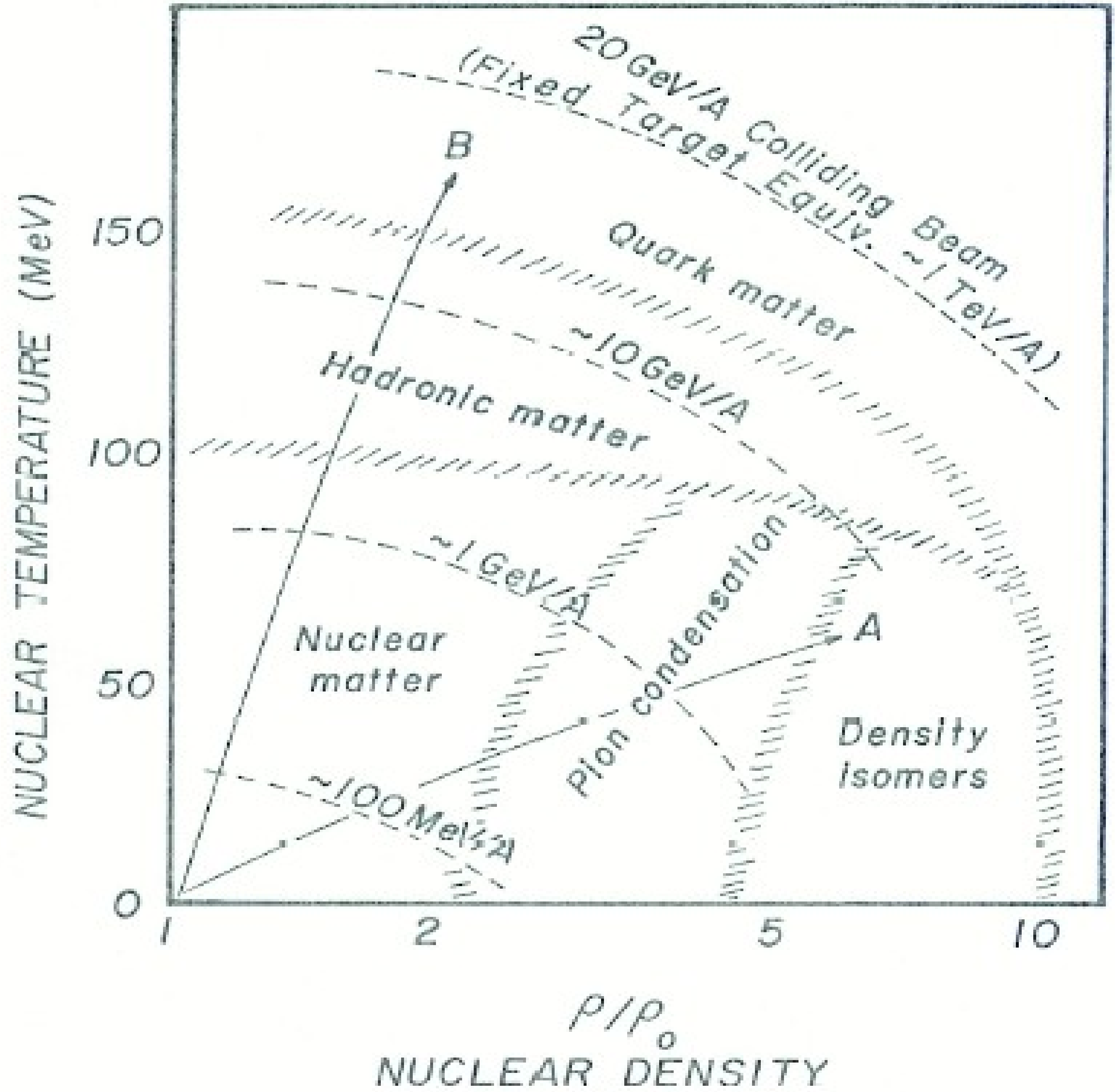
2014 Tom W. Bonner Prize in Nuclear Physics Recipient

William A. Zajc
Columbia University

"For his contributions to Relativistic Heavy-Ion Physics, in particular for his leading role in the PHENIX experiment, as well as for his seminal work on identical two-particle density interferometry as an experimental tool."

Nuclear Collisions From MeV/A to TeV/A: From Nuclear to Quark Matter
Int. Conf. on Nucleus-Nucleus Collisions, Est Lansing, 1982 , NPA400

Discovery Potential of AA was very high



I really became interested in ultra-rel AA when I started to compile cosmic ray data (MG, LBL-14512, LBL-15175 (1982))

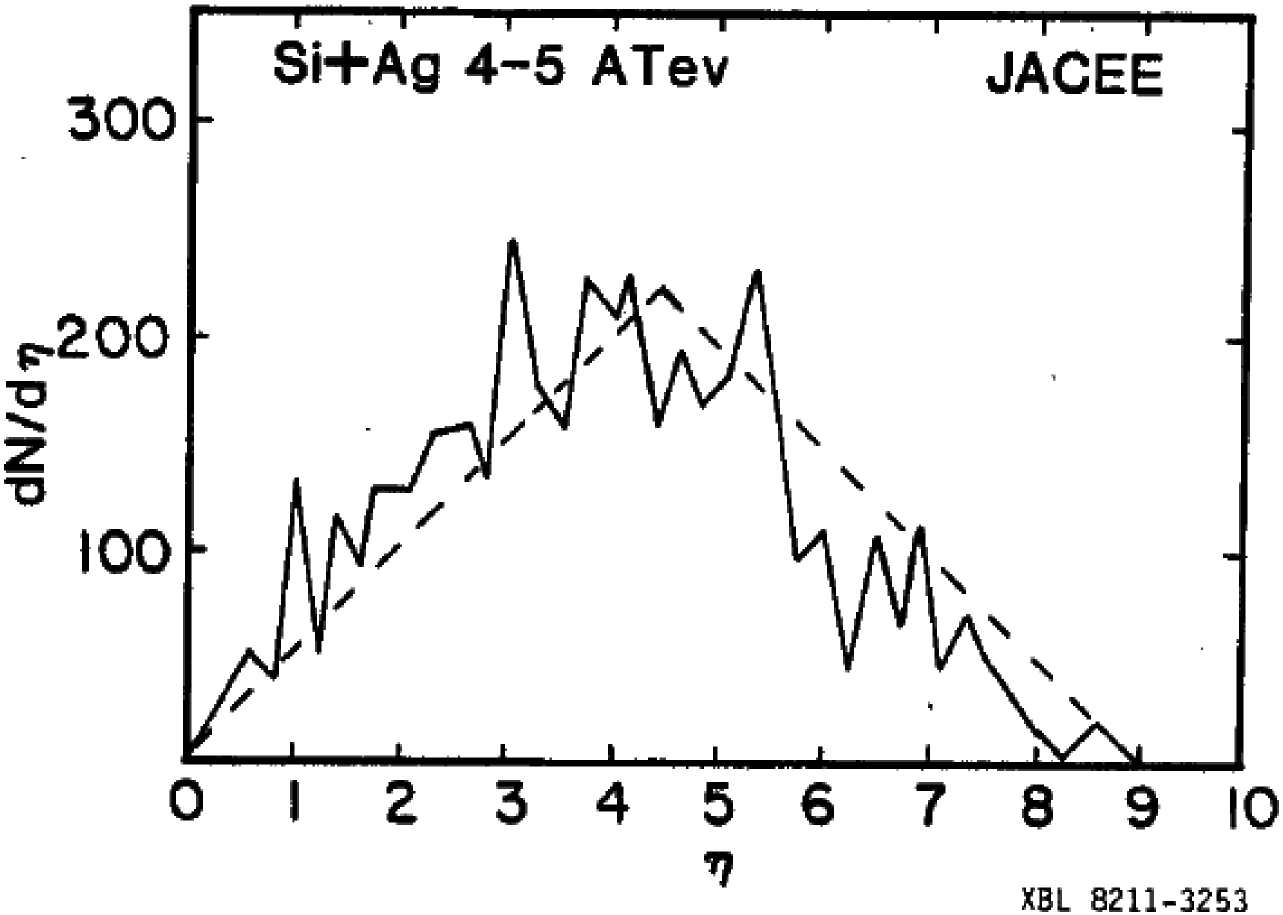


Fig. 5 Pseudo rapidity distribution[12] of Si (4 -5 ATeV) + Ag → 1000 charges + X. The most spectacular nuclear collision ever recorded! Dashed triangle is to guide the eye.

Note that in the central region ($\eta \sim 4$), $dn_{ch}/dy \sim 200$ is observed! This leads, assuming $\langle n_{\pi^0} \rangle = \langle n_{ch} \rangle / 3$, to

$$\epsilon_{max}\ (\text{JACEE}) \sim 3\ \text{GeV/fm}^3 \quad (20)$$

.~ **20 X nuclear density !**

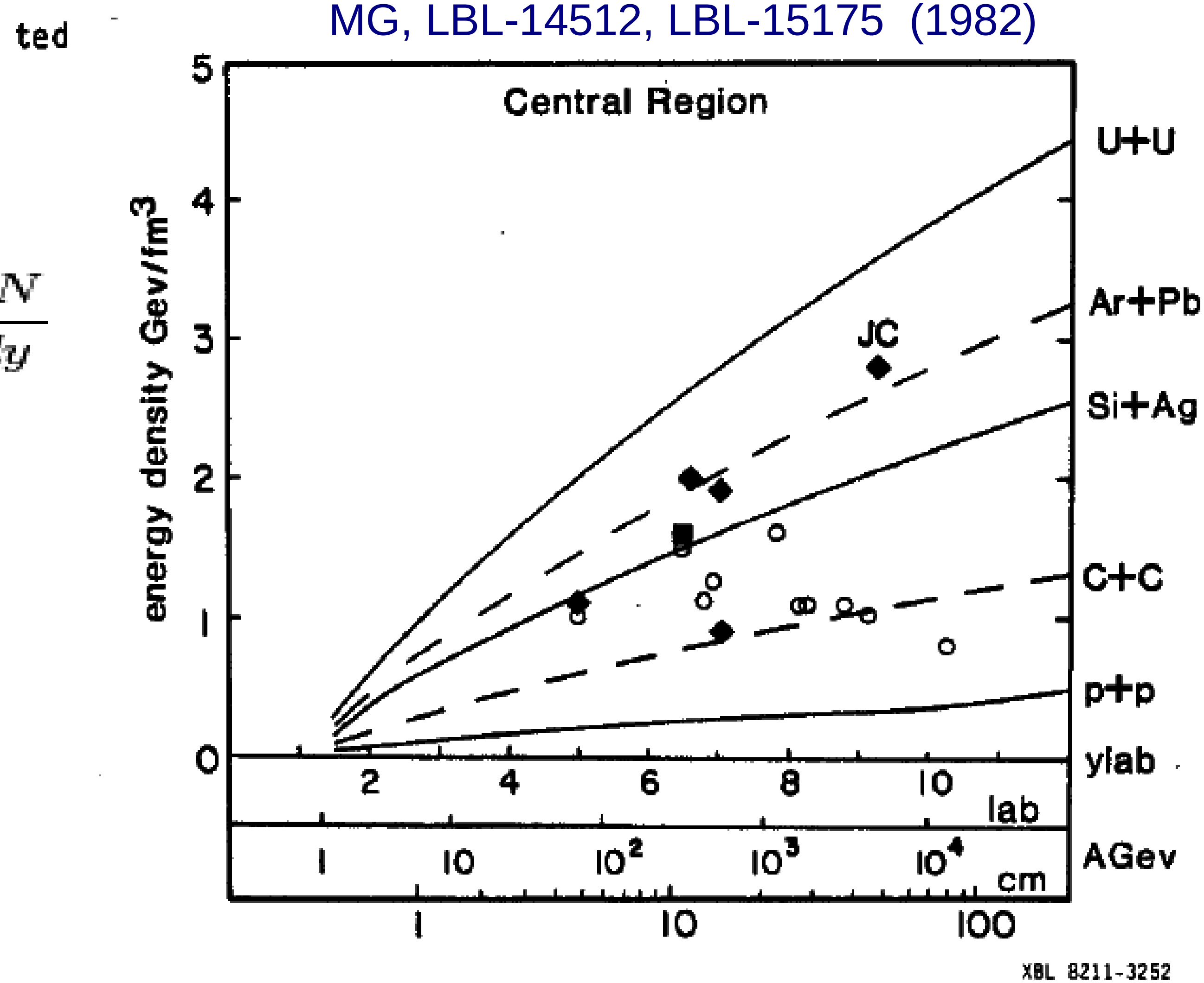
My 1982 compilation initial central energy density from the then few known cosmic ray events

Bjorken's
Inside-Outside
Energy density
At formation time

$$\left(\frac{\mathbf{E}}{\mathbf{V}}\right)_{\mathbf{form}} = \frac{\mathbf{m}_\mathbf{T}^2}{\pi \mathbf{R}^2} \frac{dN}{dy}$$

Larry and I used such estimates to support G. Baym's 1983 NSAC LRP case for RHIC construction

MG, LBL-14512, LBL-15175 (1982)



Maximum energy density achieved in low baryon density regions[14] (midrapidity). Eq. (19) was used to convert measured multiplicities [12,13] into proper energy densities. Diamonds correspond to Si + Ag, square to Ar + Pb, open circles to "light" (α, B, C, N) + Ag collisions. Theoretical estimates for various systems are based on eqs. (19,21) using tube-tube geometry as discussed in text.

Between 1984 and 2004 we worked on

Deflagrations and Detonations as a Mechanism of Hadron Bubble Growth in Supercooled Quark Gluon Plasma
MG, K. Kajantie, H. Kurki-Suonio , Larry D. McLerran NPB237 (1984)

Yang-Mills radiation in ultrarelativistic nuclear collisions
MG, Larry D. McLerran PRCC56 (1997)

New forms of QCD matter discovered at RHIC
MG, Larry McLerran Nucl.Phys. A750 (2005) 30-63

We occasionally fought on opposite sides of gedanken debates over

Initial State (CGC+Glasma) versus Final State (Perfect Fluid sQGP)

Based on different interpretations of RHIC and LHC
p+p, p+A and A+A experimental data

http://www.osti.gov/scitech/biblio/15007997

BNL-72391-2004
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 62

New Discoveries at RHIC

May 14-15, 2004

Organizers:

Wit Busza, MIT
Miklos Gyulassy, Columbia University
Larry McLerran, BNL

Nuclear Physics A750, Issue 1, Pages 1-172 (21 March 2005)

Quark-Gluon Plasma. New Discoveries at RHIC: Case for the Strongly Interacting Quark-Gluon Plasma. Contributions from the RBRC Workshop held May 14-15, 2004

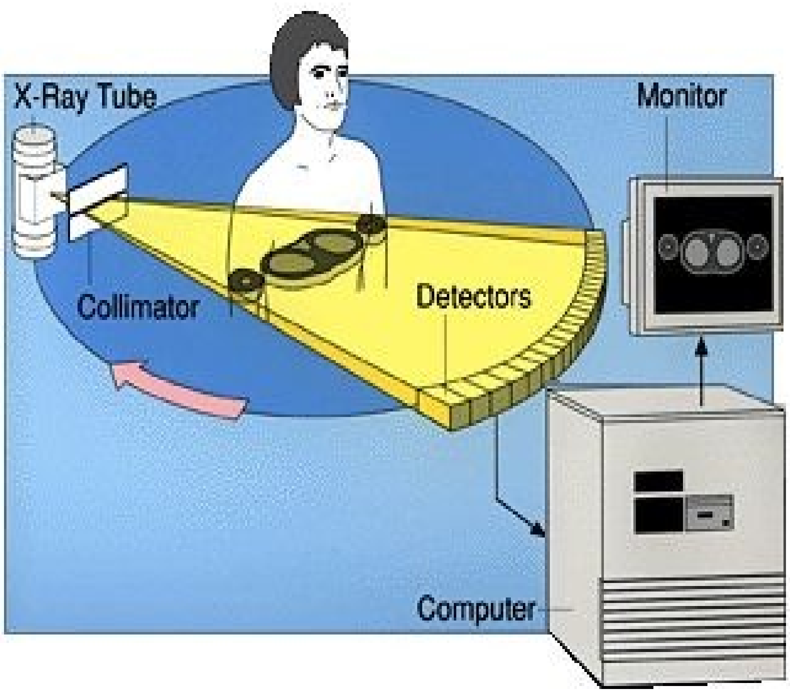
The Theoretical Case for sQGP discovery at RHIC

The Experimentalist case was presented by BRAHMS (Bearden), PHOBOS (Busza), PHENIX (Zajc), STAR (Snellings)

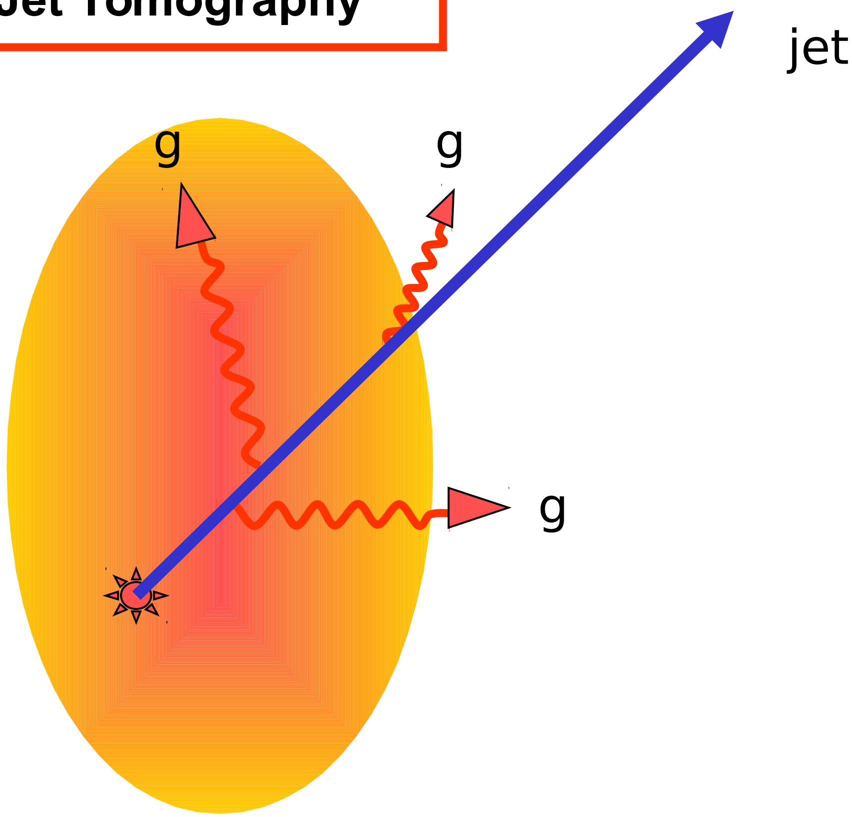
Jet Quenching and Tomography of the sQG(M)P

(X.N. Wang, P. Levai, I.Vitev, M. Djordjevic, A.Adil, S. Wicks, W. Horowitz, A.Ficnar, A, Buzzatti, J. Xu, J. Liao, MG)

Medical Tomography



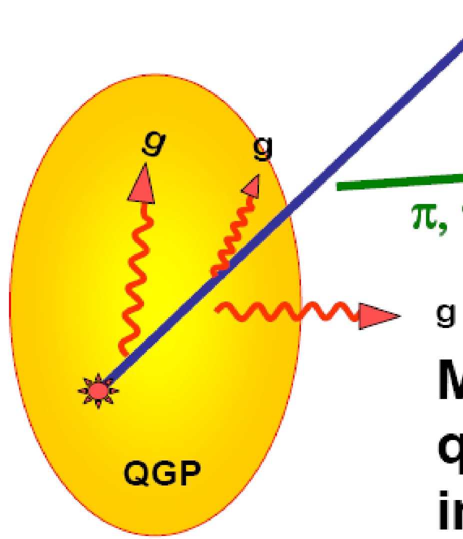
Jet Tomography



$$\Delta E_{GLV} \propto C_2 \alpha_s^3 \int dt\, t\, \rho(t\, ,\, r(t))$$

Measure of spacetime evolution of the plasma density

Jet Tomography of A+A



Quark or Glue Jet probes:

$(\eta,\ p_T,\ \phi - \phi_{reac},\ M_Q)_{init}$

Hadron jet fragments:

$(\eta,\ p_T,\ \phi - \phi_{reac})_{final}$

Measurements of hadronic quenching patterns provides information about QGP density

a) $\Delta E^{rad} \propto \alpha_s^3 \int d\tau\, \tau\, \rho_{QGP}(\tau, \vec{r}(\tau))\, Log\left(\frac{E_{Jet}}{\mu^2 L}\right)$

b) $\Delta E^{elas} \propto \alpha_s^2 \int d\tau\, \rho_{QGP}^{2/3}(\tau, \vec{r}(\tau))\, Log\left(\frac{T\, E_{Jet}}{M(T)}\right)$

c) $\Delta p_T^{\ 2} \propto \alpha_s^2 \int d\tau\, \rho_{QGP}(\tau, \vec{r}(\tau))\, Log\left(\frac{E_{Jet}}{\mu}\right)$

DNP-JPS 9.18.2005 Maui   Gyulassy 5

Detailed pQCD based multiple collision theory developed (generalizing abelian QED)

MG-Wang (1994) , MG,Levai,Vitev (2000) GLV , Djordjevic-GLV (2003), Wicks-Horowitz-DGLV (2005), Xu, Buzzatti, Ficnar, MG (2013) CUJET

BDMSP (97), Wang(00), Wiedemann (00), AMY(01), ASW(05), Majumder-Wang(2007), ...

Bjorken's pioneering work that motivated me to think about jet quenching

J.D. Bjorken , Highly Relativistic Nucleus-Nucleus Collisions: The Central Rapidity Region
(Fermilab). Jul 1982. 50 pp. Phys.Rev. D27 (1983) 140-151
FERMILAB-PUB-82-044-THY **(top cite 2306)**

J.D. Bjorken, Energy Loss of Energetic Partons in Quark - Gluon Plasma: Possible Extinction of High p(t) Jets in Hadron - Hadron Collisions,
(Fermilab). Aug 1982. 20 pp. FERMILAB-PUB-82-059-THY (cited 124)

$$\frac{dE}{dx} \simeq \left(\frac{2}{3}\right)^{\pm 1} \varepsilon^{1/2} \left(\log \frac{4ET}{M^2}\right) \mathrm{GeV/f} \qquad (\hbar c)^2$$

Elastic energy loss
ε ιn GeV/fm3 units

$$\Delta p_T = \begin{cases} 30\ \mathrm{GeV} & \text{gluon} \\ 13\ \mathrm{GeV} & \text{quark} \end{cases}$$

$\hbar c=1$

This is quite sufficient to quench low-p_T jets!!

Our estimates suggested elastic en loss was too small even in AA

Quark Damping and Energy Loss in the High Temperature QCD
Markus H. Thoma, MG, NPB351 (1991) 491

$$\Delta p_T^{el}(quark) \approx 1GeV \ll p_T \sim 10GeV$$

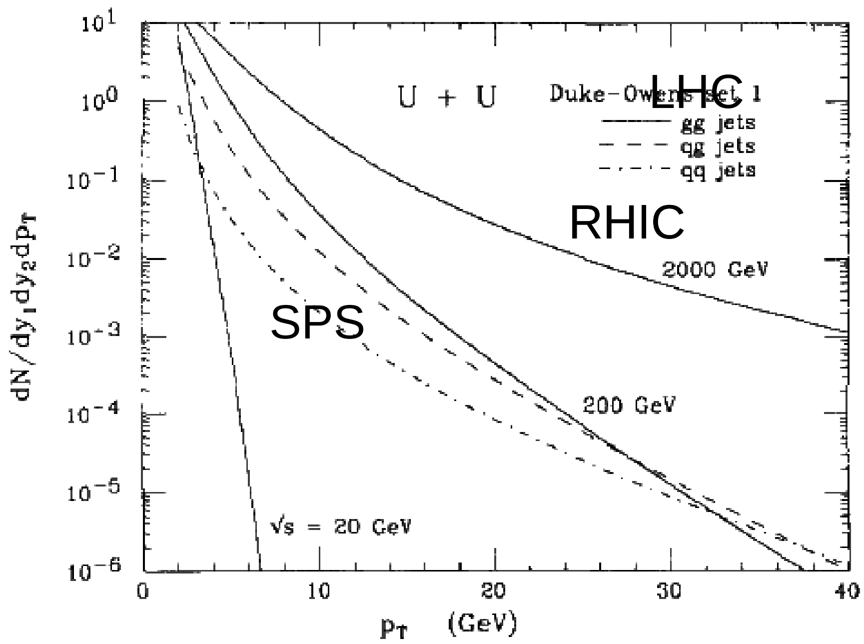
$\hbar c=0.197$

Jet Quenching in Dense Matter, MG, M. Plumer, PLB243 (1990)

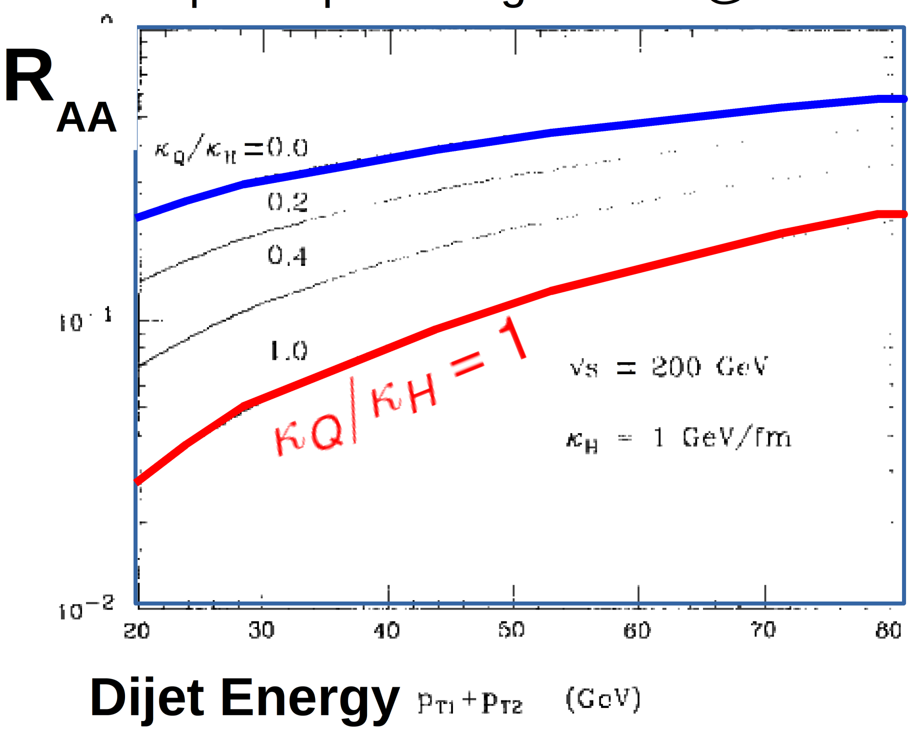
$R_{AA} = (\text{Number dijets in AA})/(\text{Geom Scaled Number of dijets in pp})$

Vary energy loss tension dE/dx = 0 – 1 GeV/fm

pQCD Initial Jet pT spectra in pp



Diquark quenching in U+U @ RHIC



We find that jet quenching in heavy nuclei is expected to reduce the rate of back-to-back jets with $E_{tot} \sim 30$ GeV by an order of magnitude.

Valuable discussions with W. Geist, J.W. Harris, K. Kajantie, L.D. McLerran, A. Mueller, S. Nagamiya, A. Poskanzer, T.J. Symons and X.N. Wang are gratefully acknowledged.

 + 

=> HIJING and Applications

In 1989 we started work on a pp , pA, AA exclusive event open source Monte Carlo generator for use by experimentalist to design detectors at RHIC and LHC and by theorists to explore observable consequences of nonlinear initial and final state effects consistent with known pp data and known lower (AGS and SPS) energy pA and AA data.

1) HIJING: A Monte Carlo model for multiple jet production in p p, p A and A A collisions, Xin-Nian Wang, Miklos Gyulassy Phys.Rev. D44 (1991) 3501-3516 (Top Cite by 1103)

2) Gluon shadowing and jet quenching in A + A collisions at s**(1/2) = 200-GeV, Xin-Nian Wang , Miklos Gyulassy
Phys.Rev.Lett. 68 (1992) 1480-1483 (Top Cite by 641)

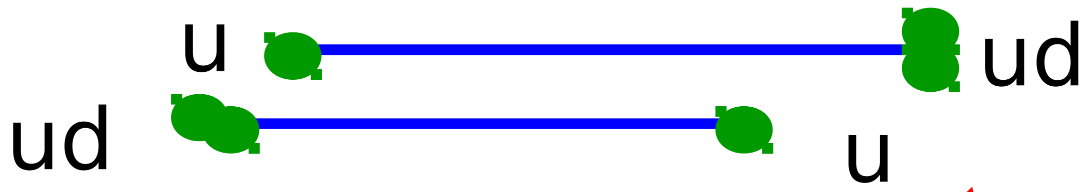
3) HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions, Miklos Gyulassy, Xin-Nian Wang (LBL, Berkeley), Comp.Phys.Comm. 83 (1994) 307 (Top Cite by 597)

HIJING A+B Multiproduction Model

1) Soft Beam Jet Fragmentation

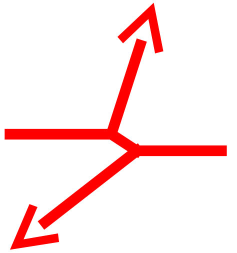
(string phenomenology, LUND, DPM)

"Pomeron"

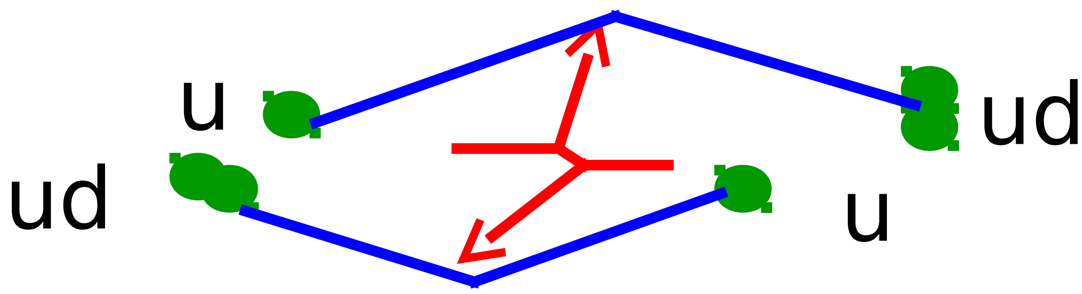


2) Hard pQCD $p_T > p_0$ PYTHIA

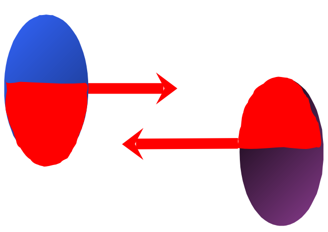
(Sjostrand)



(1+2) Hard pQCD Hadronized by Strings

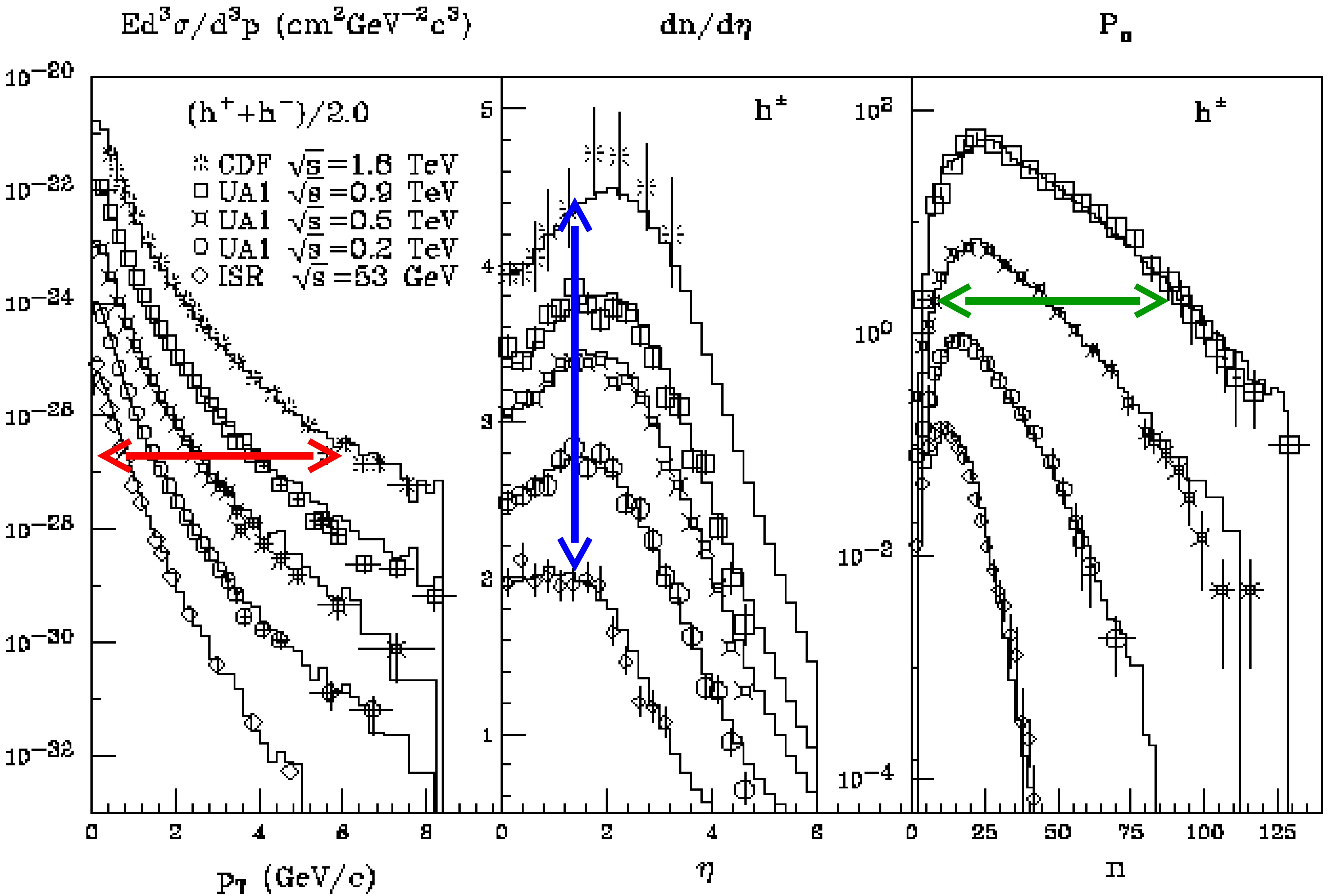


3) A+A Glauber Geometry



HIJING Soft+Hard Dynamics in p+p

XN Wang, MG 1991



HIJING= T_{AB}(b) (pQCD pt>p0)$_{Pythia}$ + N_{part}(b)(String Phenom)$_{LUND,DPM}$

X-N Wang, MG: HIJING

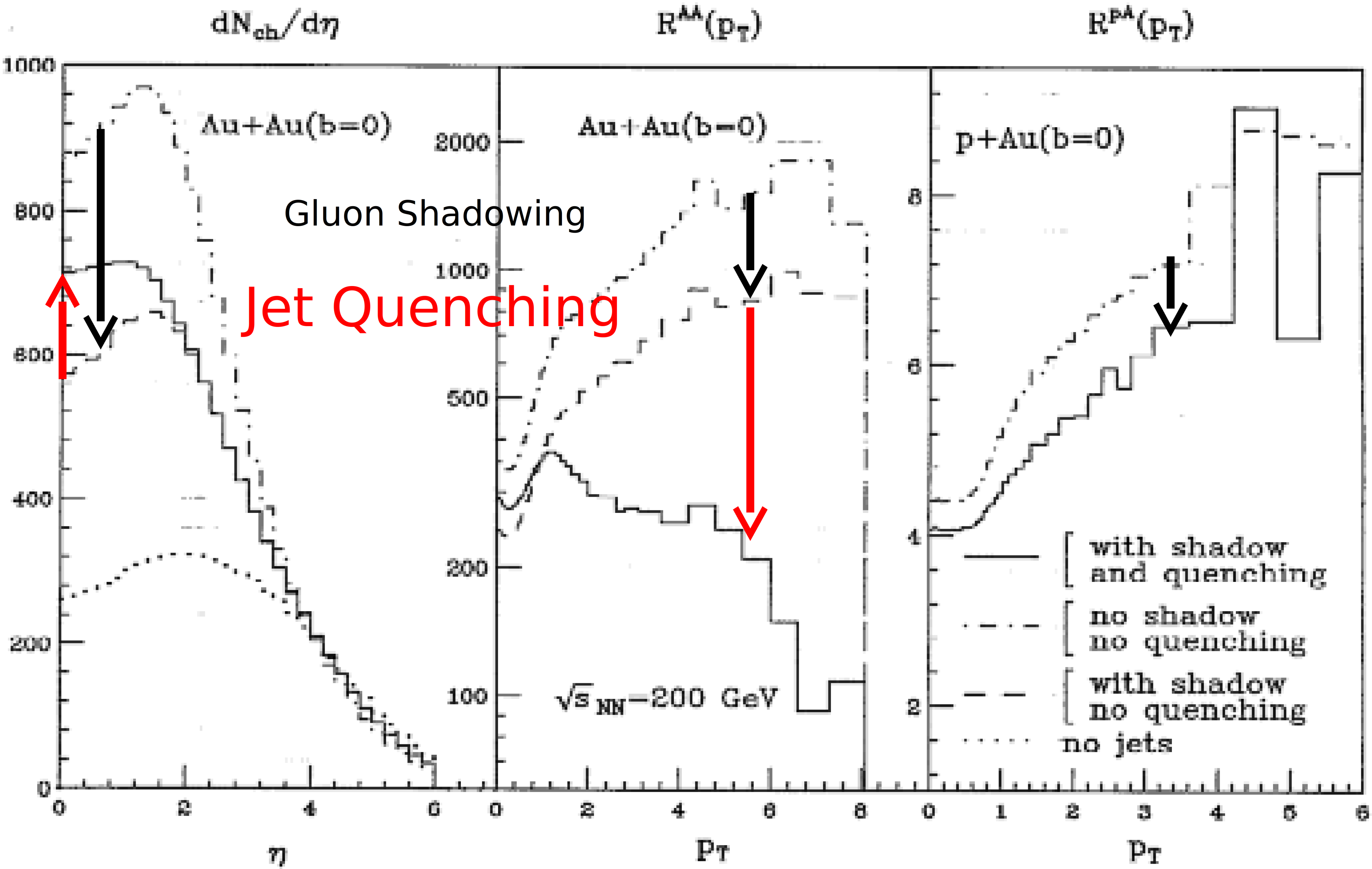
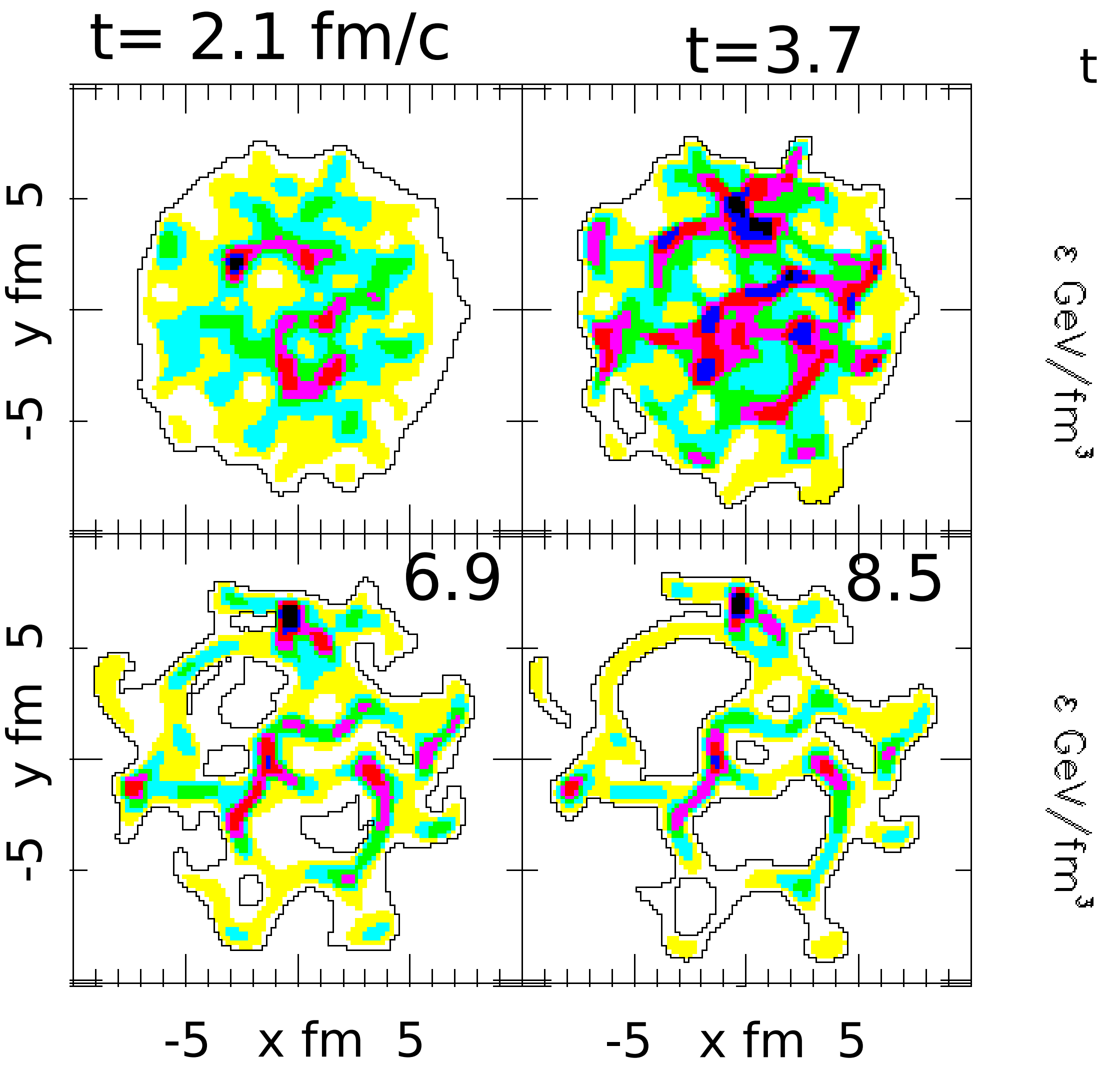


FIG. 1. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and $p+\mathrm{Au}$ collisions on minijet production (dash-dotted line), gluon shadowing (dashed line), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and $dE/dl = 2$ GeV/fm with $\lambda_s =$ M.Gyulassy $R^{AB}(p_T)$ is the ratio of the inclusive p_T spectrum of charged hadrons in $A+B$ collisions to that of $p+p$.

Turbulent Glue Scenario = HIJING +Hydro



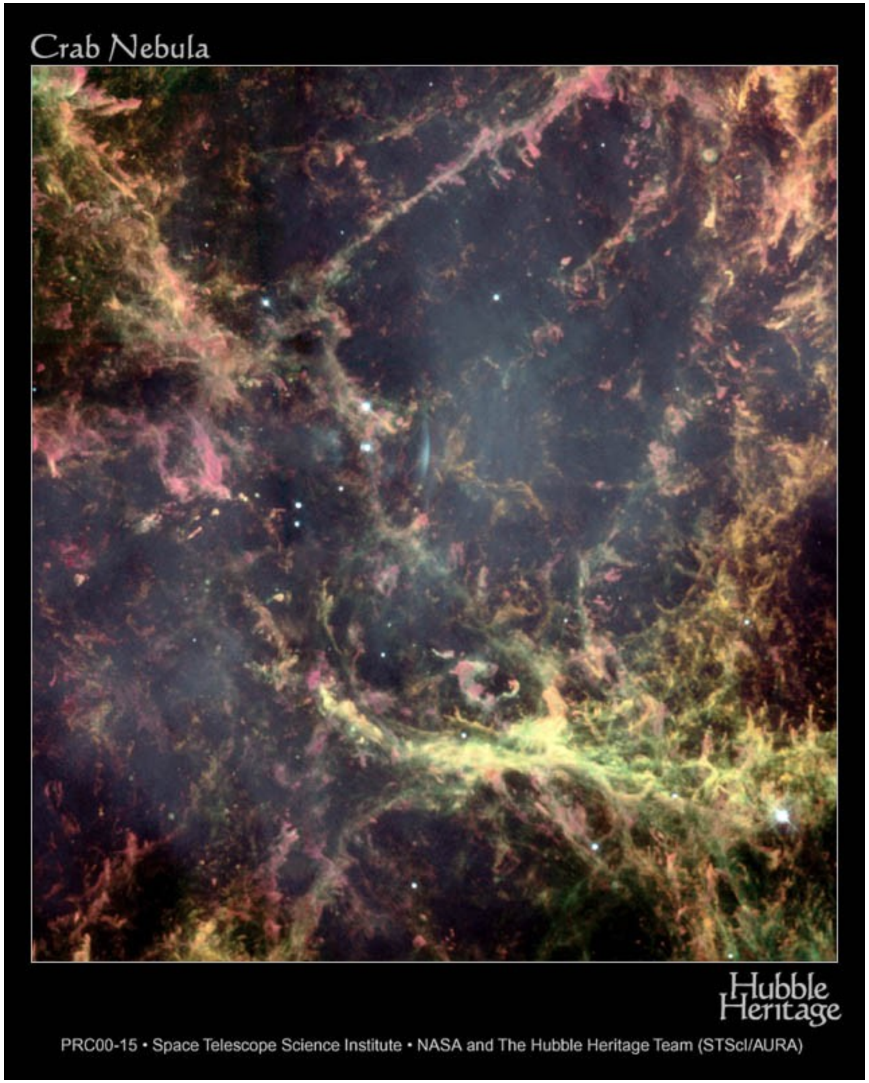
D. Rischke, B. Zhang, MG 1997

Mini jet hot spots seed

Hadronic Filaments and Shells

In A+A

t= 947 years=10^{36} fm/c, dx ~1 light year



Filaments in the Crab

supernova

Theory of Non-abelian Radiative Energy Loss

QCD Bethe-Heitler

• G. Bertsch, F. Gunion, Phys. Rev. **D25** 746 (1982)

QGP Multiple Collision

• M. Gyulassy, X.-N. Wang, Nucl. Phys. **B420** 583-614 (1994); Phys. Rev. **D51** 3436-3446 (1995)

"Thick" Plasma Limit

$$\Delta E = \alpha \sqrt{\omega_c E} \; : \; 10 \text{GeV} \left(\frac{L}{5 \text{fm}} \right)$$

• R. Baier, Yu. Dokshitzer, A. Mueller, S. Peigne, D. Schiff, Nucl. Phys. **B483** 291-320 (1997); Phys. Rev. **C58** 1706-1713 (1998)

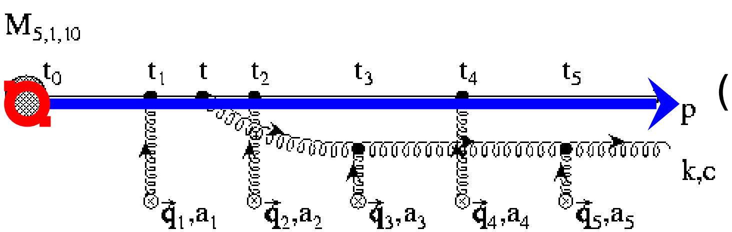
• B. Zakharov, JETP Lett. **65** 615-620 1997, JETP Lett. **73** 49-52 (2001)

"Thin" Plasma Limit

L/λ_g Opacity Expansion

• M. Gyulassy, P. Levai, Ivan Vitev, NPB 595 371-419 (2001); Phys. Rev. Lett. **85** 5535-5538 (2000)

• U. Wiedemann, Nucl. Phys. **B588** 303-344 (2000), Nucl. Phys. **B582** 409-450 (2000)



$(1-x)E$

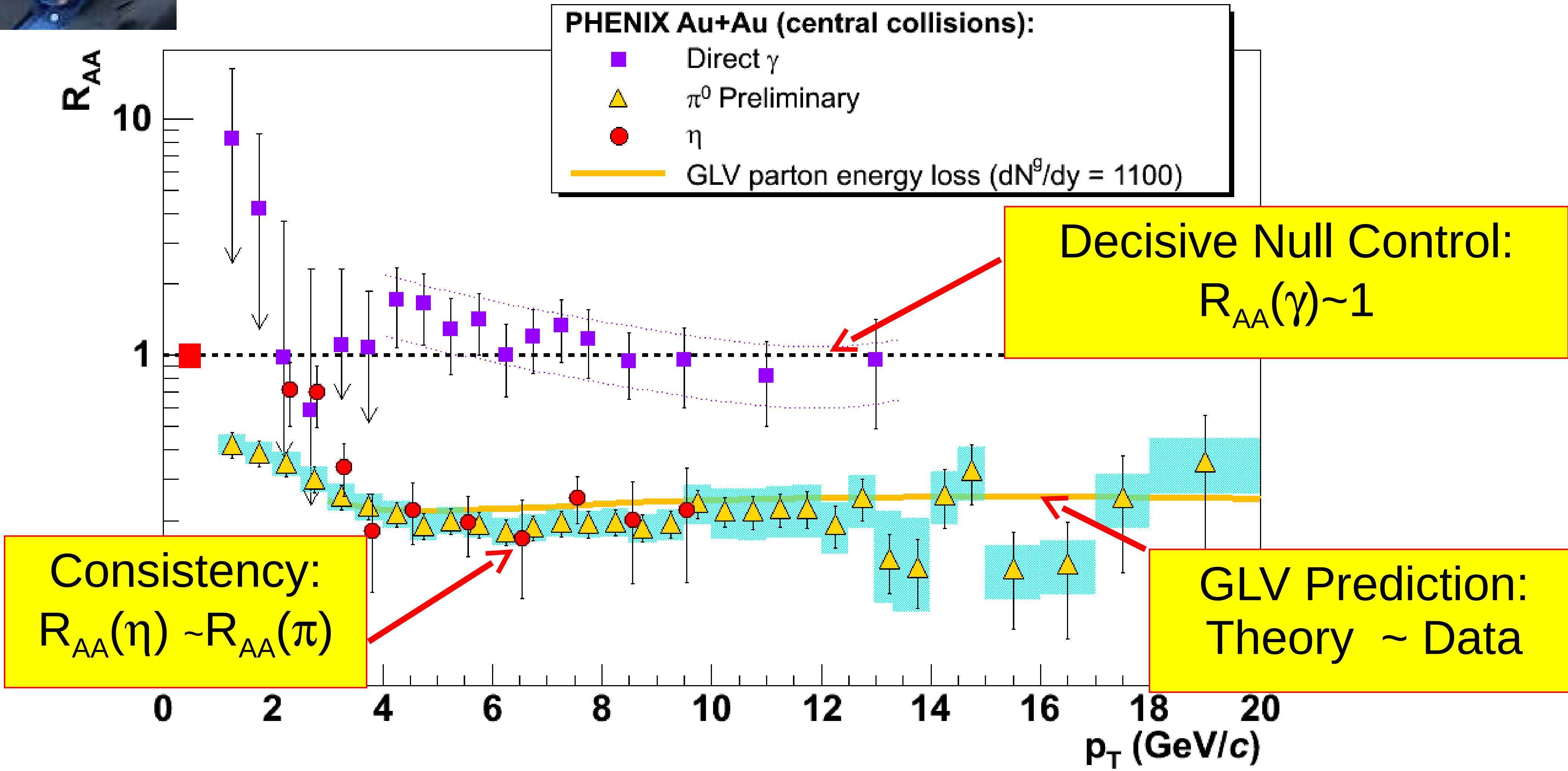
xE

Analytic at any order $(L/\lambda)^n$

$$\Delta E^{(1)} \approx \frac{9}{4} \alpha_s^3 \pi C_R \left(\frac{1}{\pi R^2} \frac{dN_g}{dy} \right) \left\{ \text{Log} \frac{2E}{\mu^2 L} \right\} L(\phi)$$

High pT tomography of d + Au and Au+Au at SPS, RHIC, and LHC
Ivan Vitev, MG, PRL 89 (2002) 252301

GLV prediction of RAA vs PHENIX



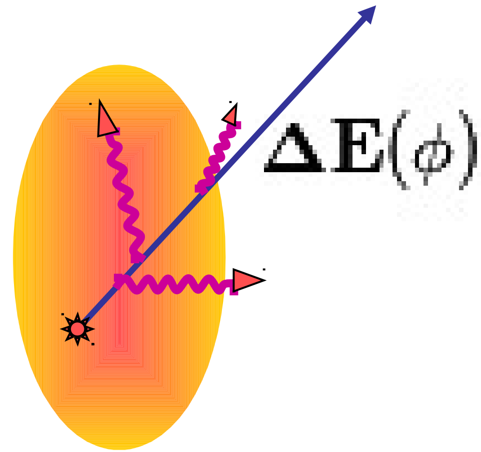
Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c
Common suppression for π^0 and η; it is at partonic level

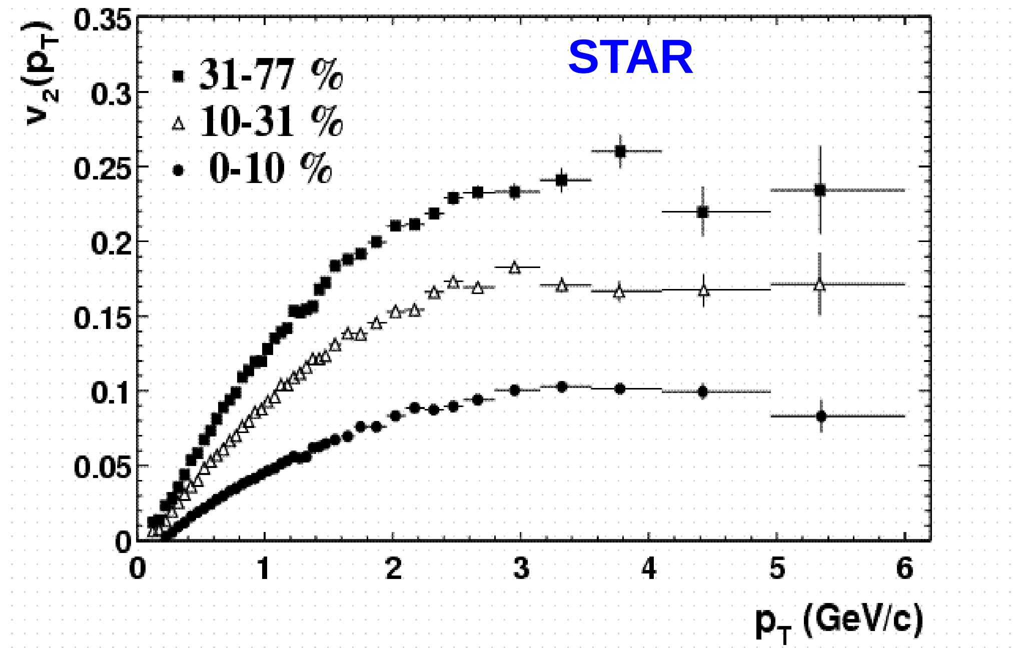
ε > 15 GeV/fm^3 ~ 100 ground state nuclei

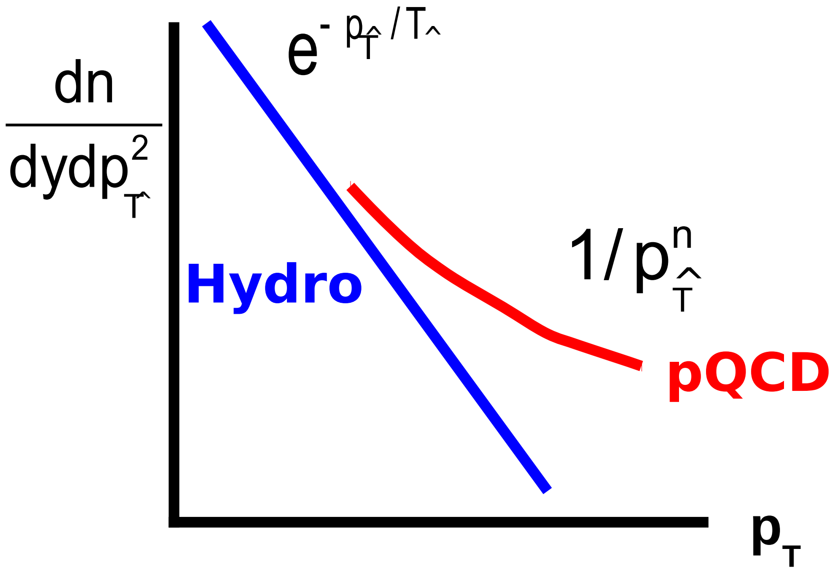
Elliptic Jet Tomography

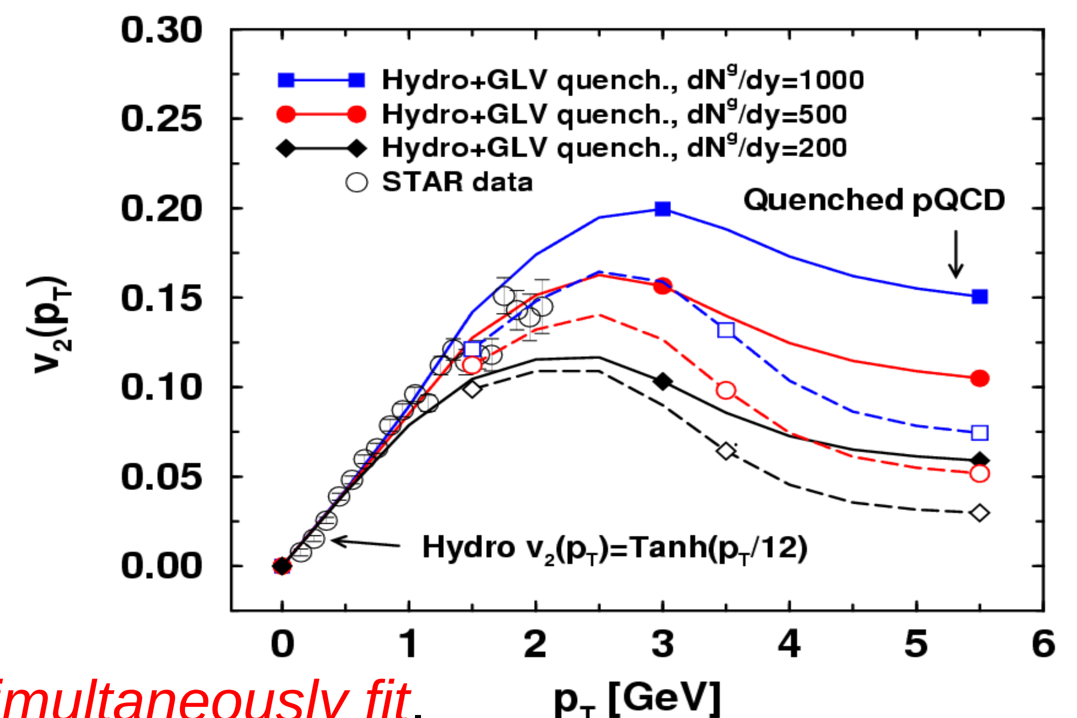
MG, I. Vitev and X.N. Wang, PRL86(01)

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









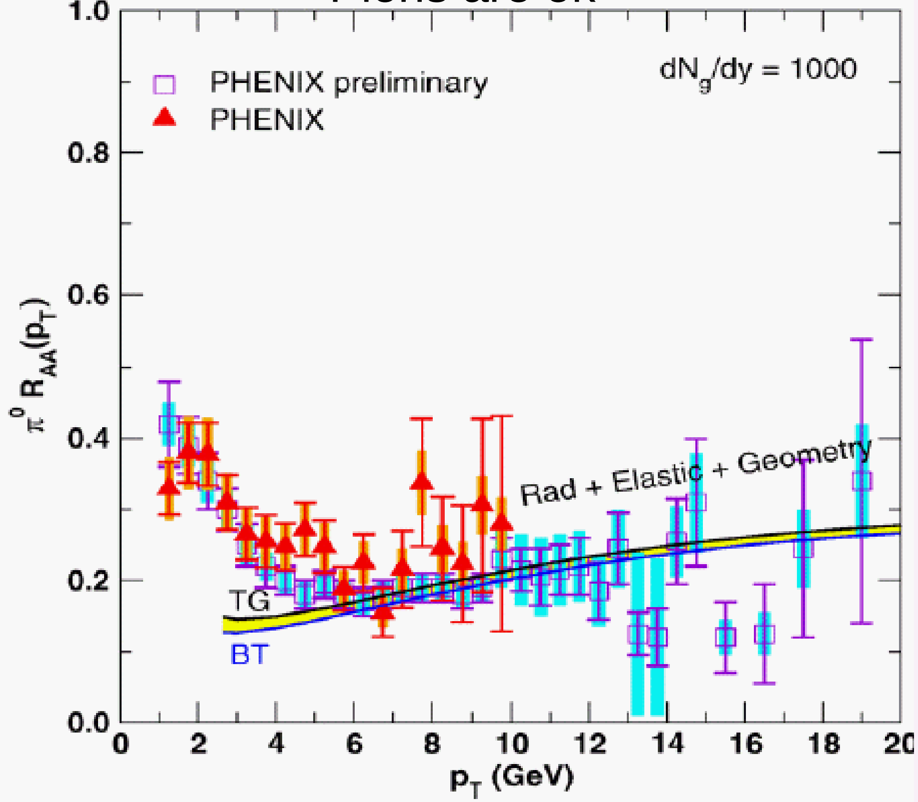
We found (until recently 2014!)
that RAA and v2 data *could not be simultaneously fit*.

This jet v2 problem is now solved (J.Xu, J. Liao, MG) by wQGP --> **sQGMP**

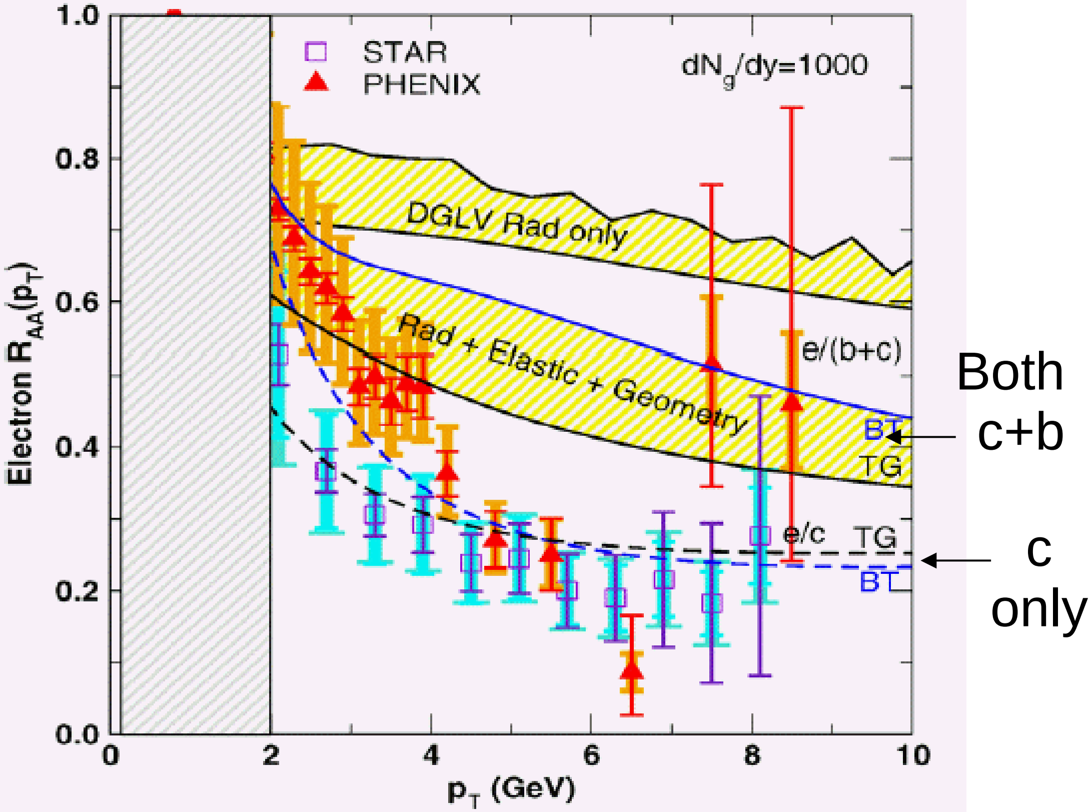
The RHIC Heavy quark (c+b → e +X) Puzzle

WHDG: S.Wicks, W. Horowitz, M. Djordjevic, M.Gyulassy, NPA784 (2007) 426

Pions are ok



But Heavy quarks are not!



Electron data seemed to falsify pQCD HQ dynamics

(1) Why are bottom quark jets suppressed ?

(2) How can α_s (Q) lead to such strong coupling?

sQGMP now also solves this probelem (J.Xu, J. Liao, MG 2015)

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

A quantitative test of sQGMP generalization of wQGP In the QCD transition range 150-250 MeV

Jiechen Xu, Jinfeng Liao, Miklos Gyulassy

(Submitted on 13 Nov 2014 (v1), last revised 31 Mar 2015 (this version, v2))

We utilize a new framework, CUJET3.0, to deduce the energy and temperature dependence of jet transport parameter, $\hat{q}(E > 10\ \mathrm{GeV}, T)$, from a combined analysis of available data on nuclear modification factor and azimuthal asymmetries from RHIC/BNL and LHC/CERN on high energy nuclear collisions. Extending a previous perturbative-QCD based jet energy loss model (known as CUJET2.0) with (2+1)D viscous hydrodynamic bulk evolution, this new framework includes three novel features of nonperturbative physics origin: (1) the Polyakov loop suppression of color-electric scattering (aka "semi-QGP" of Pisarski et al) and (2) the enhancement of jet scattering due to emergent magnetic monopoles near T_c (aka "magnetic scenario" of Liao and Shuryak) and (3) thermodynamic properties constrained by lattice QCD data. CUJET3.0 reduces to v2.0 at high temperatures $T > 400$ MeV, but greatly enhances $\hat{q}$ near the QCD deconfinement transition temperature range. This enhancement accounts well for the observed elliptic harmonics of jets with $p_T > 10$ GeV. Extrapolating our data-constrained $\hat{q}$ down to thermal energy scales, $E \sim 2$ GeV, we find for the first time a remarkable consistency between high energy jet quenching and bulk perfect fluidity with $\eta/s \sim T^3/\hat{q} \sim 0.1$ near T_c.

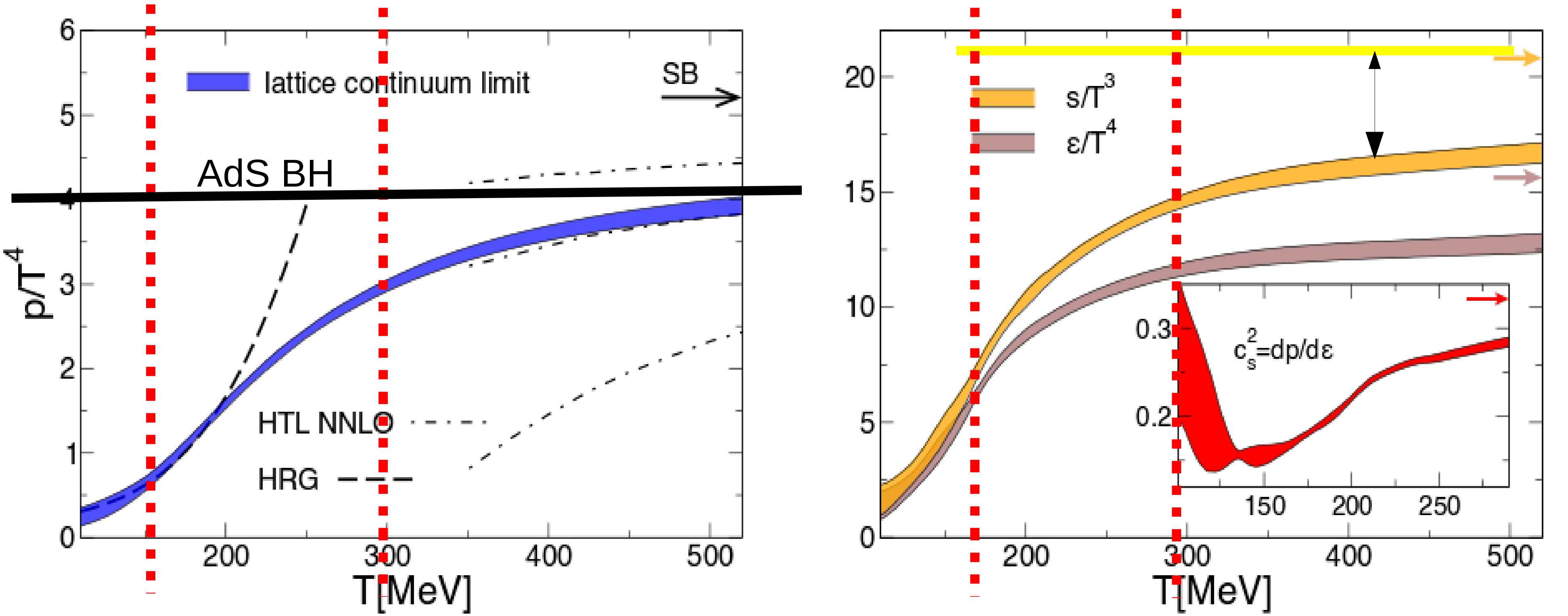
Comments: 6 pages, 4 figures; v2: major text revisions, title and abstract modified, typos corrected, references added

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)

Cite as: **arXiv:1411.3673 [hep-ph]**

(or **arXiv:1411.3673v2 [hep-ph]** for this version)

. Continuum EoS for QCD with Nf=2+1 flavors



In the QCD transition temperature range 150 < T<300 MeV the sQGP is

(1) *NOT* a Hadron Resonance Gas (HRG)

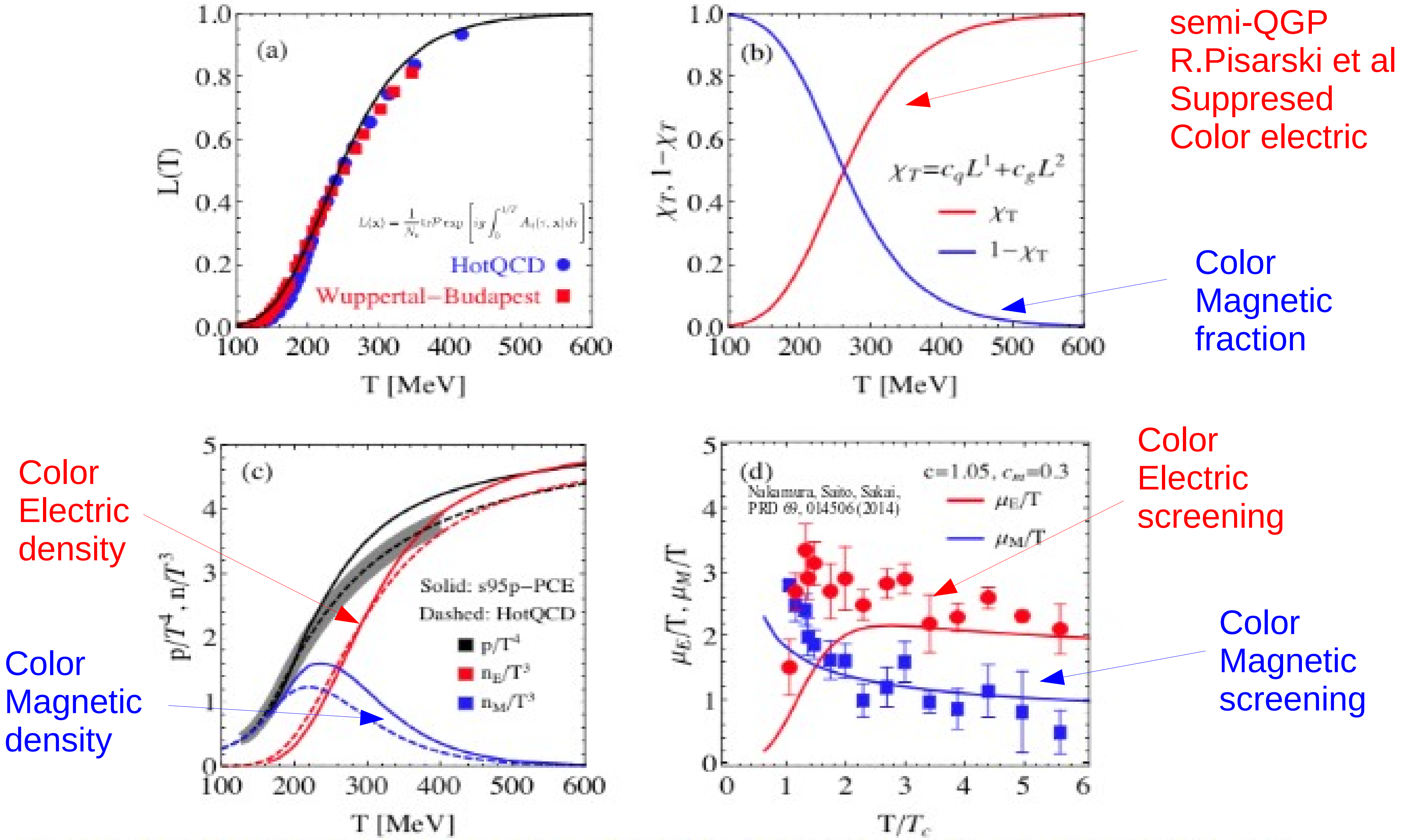
(2) *NOT* a perturbative Q+G plasma of quasi free quarks and gluons

(3) *NOT* a conformal AdS/CFT Black Hole

(4) Could it be a semi-QGP + Mag monopole Plasma (sQGMP) ?

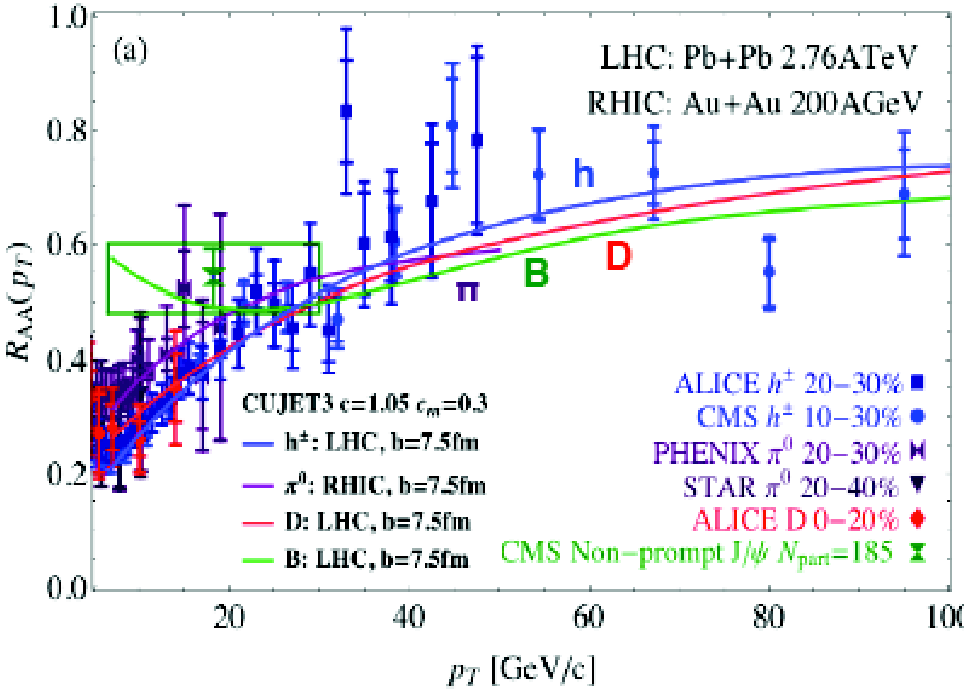
Non-Perturbative Physics in the QCD Cross-Over transition temperature range

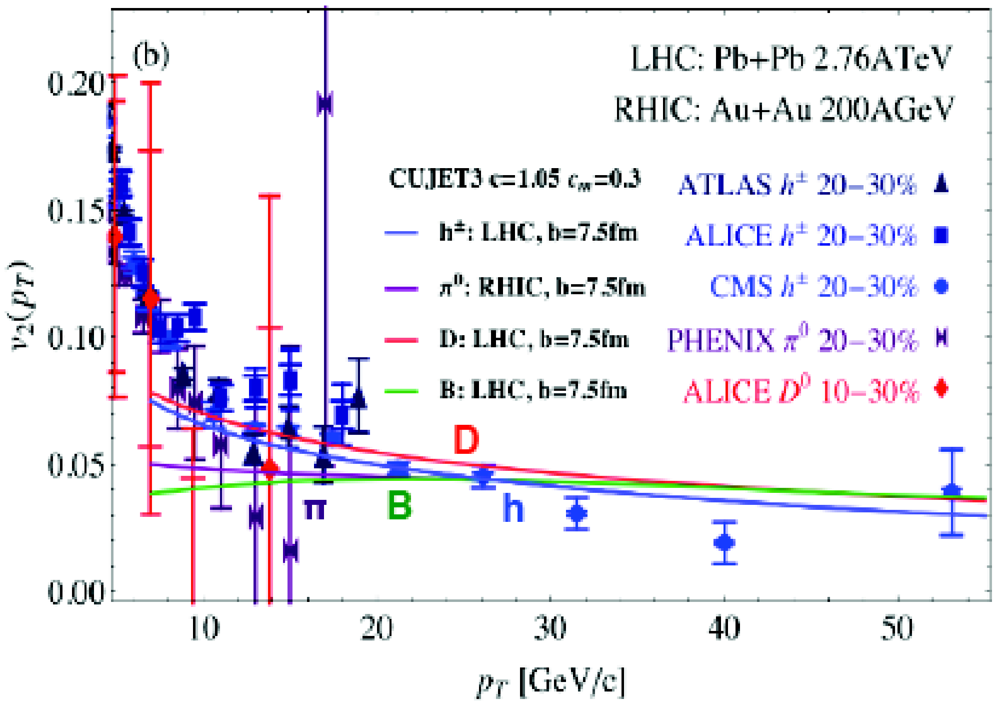
Lattice Constraints: Polyakov Loop, EOS, Screening Masses



- The CUJET3.0 implementations of electric and magnetic components are well constrained by available lattice data. The only adjustable parameter in this model is “c”.

CUJET3.0 simultaneously describes high pT $(R_{AA}+v_2)^*(\text{light + heavy})^*(\text{RHIC+LHC})$





The combined set of observables

$(R_{AA}+V_2)^*(\text{RHIC+LHC})^*(\text{pion+D+B})$

are consistently accounted for (within present experimental errors) in the CUJET3.0 framework using lattice data constrained sQGMP near Tc + pQCD jet quenching !

Jiechen Xu, Jinfeng Liao, MG arXiv 1411.3673

The Inverse connection between eta/s and the jet transport qhat(T,E) field

Jiechen Xu, Jinfeng Liao, MG arXiv:1411.3673 [hep-ph]

We now turn to the shear viscosity. As in [4–6], an estimate of shear viscosity per entropy density η/s can be derived from kinetic theory in the weak coupling limit:

Depends of composition and m.f.p. of all quasi-particles in the QGP

$$\eta/s = \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p \rangle_a \lambda_a^{tr}$$

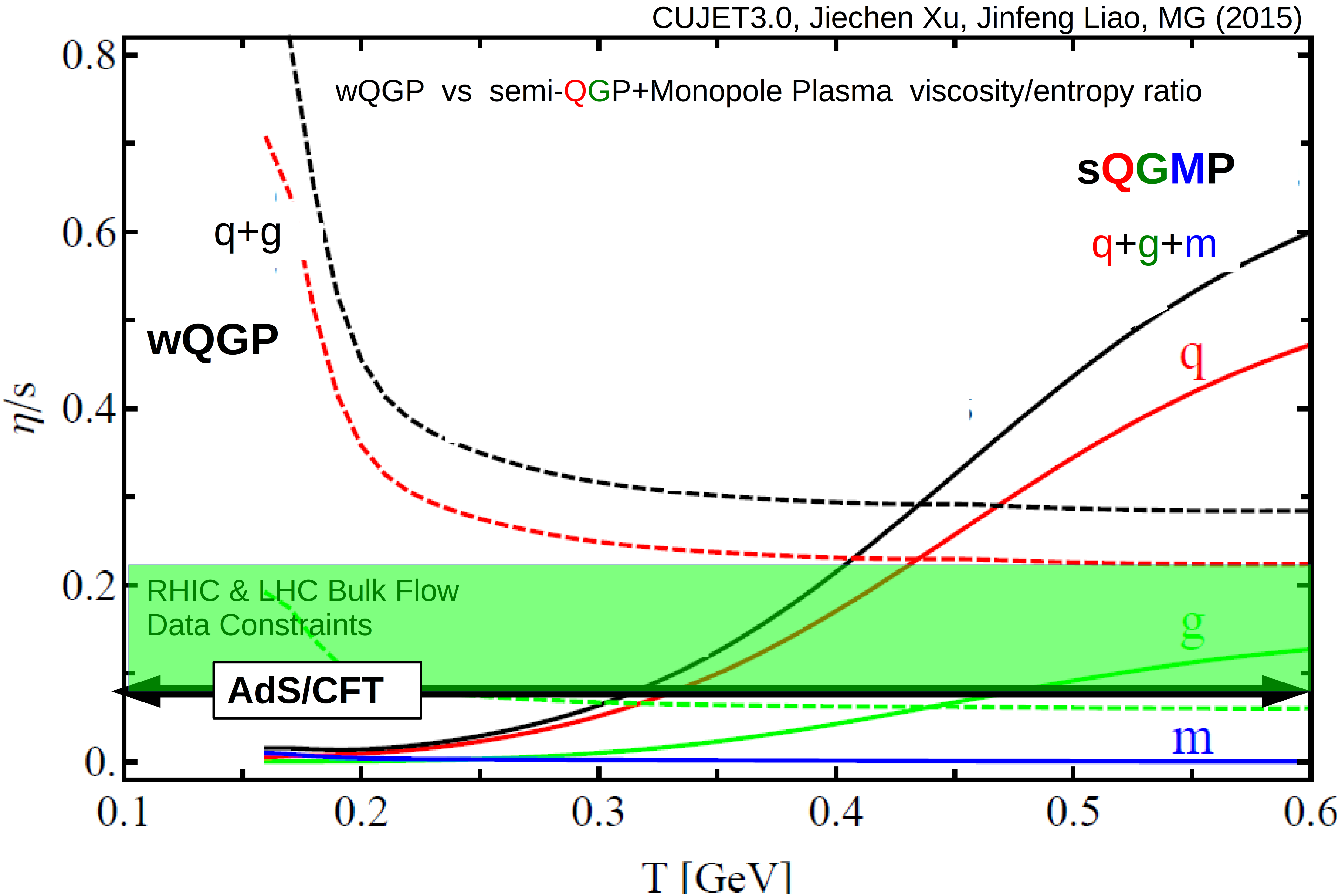
$$= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle \mathcal{S}_{ab} \rangle /2} dq^2 \frac{4q^2}{\langle \mathcal{S}_{ab} \rangle} \frac{d\sigma_{ab}}{dq^2} \right)^{-1}$$ [4,5]

★ $$= \frac{18T^3}{5s}\sum_a \rho_a / \hat{q}_a(T, E = 3T) \ .$$

[4] P. Danielewicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).

[5] T. Hirano and M. Gyulassy, Nucl. Phys. A **769**, 71 (2006).

★ [6] A. Majumder, B. Muller, and X. N. Wang, Phys. Rev. Lett. **99**, 192301 (2007).



CUJET3.0, Jiechen Xu, Jinfeng Liao, MG (2015)
wQGP vs semi-QGP+Monopole Plasma viscosity/entropy ratio
sQGMP
q+g+m
q+g
wQGP
q
g
m
RHIC & LHC Bulk Flow
Data Constraints
AdS/CFT
η/s
T [GeV]
0.8
0.6
0.4
0.2
0.
0.1
0.2
0.3
0.4
0.5
0.6

Thank You

I regard my 2015 APS Bonner prize as recognizing successful collective work with >1000 exp and theorists in the field of high energy relativistic heavy ion physics over the past 40 years.

As one of the hereby elected representatives of this field,
I am deeply grateful to my many collaborators and my Columbia University students whose efforts and insights make this field so physics rich and rewarding for me.

I thank **Xin-Nian Wang** in particular for our 25 years of close work and friendship.
I also owe special thanks to **I.Vitev, P. Levai, M. Djordjevic, W.Horowitz, S.Wicks, A.Buzzatti, A.Ficnar, and J.Xu** for our 15 year development of a quantitative theory of jet tomography.

Thanks to the >1000 experimentalists at RHIC and LHC , esp. **John Harris, Art Poszkanzer and William Zajc**, who guided our interpretations by their precise data and new discoveries that forced us to find missing physics terms and change our paradigms.

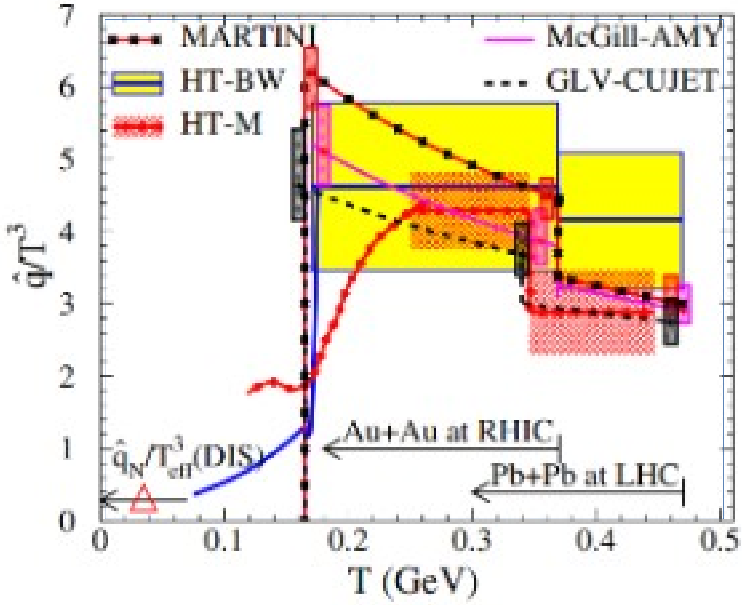
Last, but far from least, I could not have been able to do this work without the vital support and love from Gyorgyi and my three children.

I am grateful to my mother, Marianne Lindner, who immigrated to the US in 1956 from Hungary with me to be able to live and work in this free and open society.

I am happy to be reconnected to a free and open Hungary since 1989 thanks to my friends and colleagues at the MTA Wigner Research Center in Budapest.

Jet quenching parameter (qhat) and η/s

$$\hat{q} = \rho \int d^2 q_\perp q_\perp^2 \frac{d\sigma}{d^2 q_\perp}$$



JET Collaboration, PRC 90, 014909 (2014)

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \quad \begin{matrix} T = 370 \text{ MeV,} \\ T = 470 \text{ MeV,} \end{matrix}$$

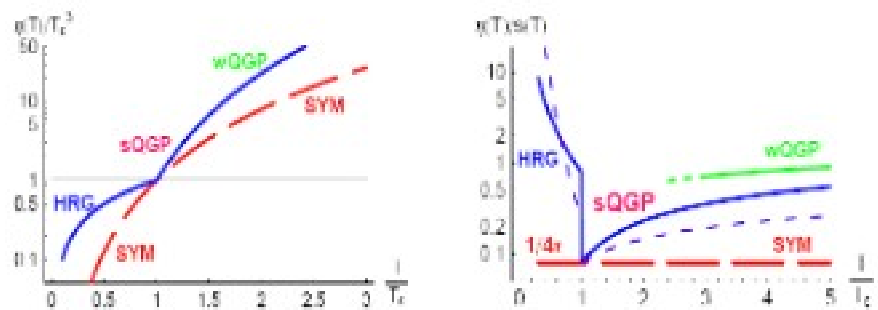
- Kinetic theory estimate of η/s from qhat

$$\begin{aligned} \eta/s &= \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p \rangle_a \lambda_a^{tr} \\ &= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle \mathcal{S}_{ab} \rangle /2} dq^2 \frac{4q^2}{\langle \mathcal{S}_{ab} \rangle} \frac{d\sigma_{ab}}{dq^2} \right)^{-1} \\ &= \frac{18T^3}{5s} \sum_a \rho_a / \hat{q}_a(T, E = 3T) \ , \end{aligned} \quad (1$$

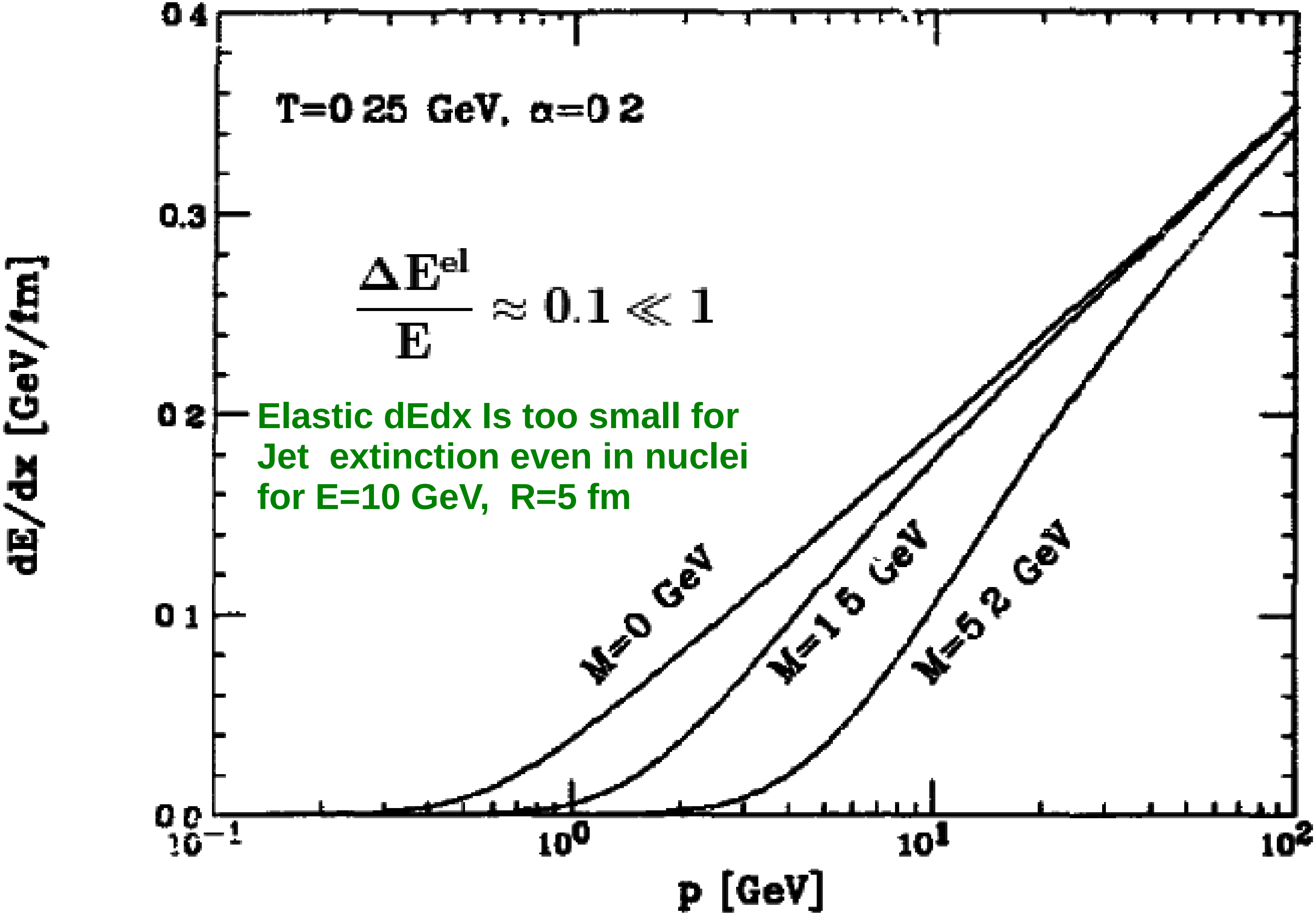
Danielewicz, Gyulassy, PRD 1985

$$\frac{\eta}{s} \left\{ \begin{matrix} \approx \\ \gg \end{matrix} \right\} 1.25 \frac{T^3}{\hat{q}} \begin{cases} \text{for weak coupling,} \\ \text{for strong coupling.} \end{cases}$$

Majumder, Muller, Wang, PRL 2007



Hirano, Gyulassy, NPA 2006



$$\frac{\Delta E^{el}}{E} \approx 0.1 \ll 1$$

Elastic dEdx Is too small for Jet extinction even in nuclei for E=10 GeV, R=5 fm

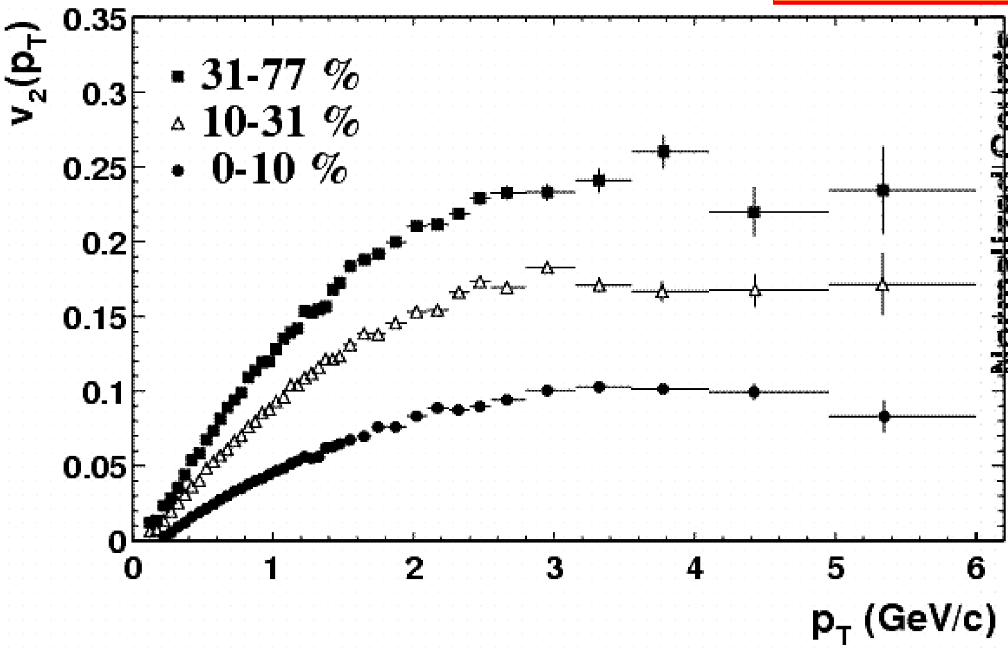
Fig 3 Energy loss for different quark masses

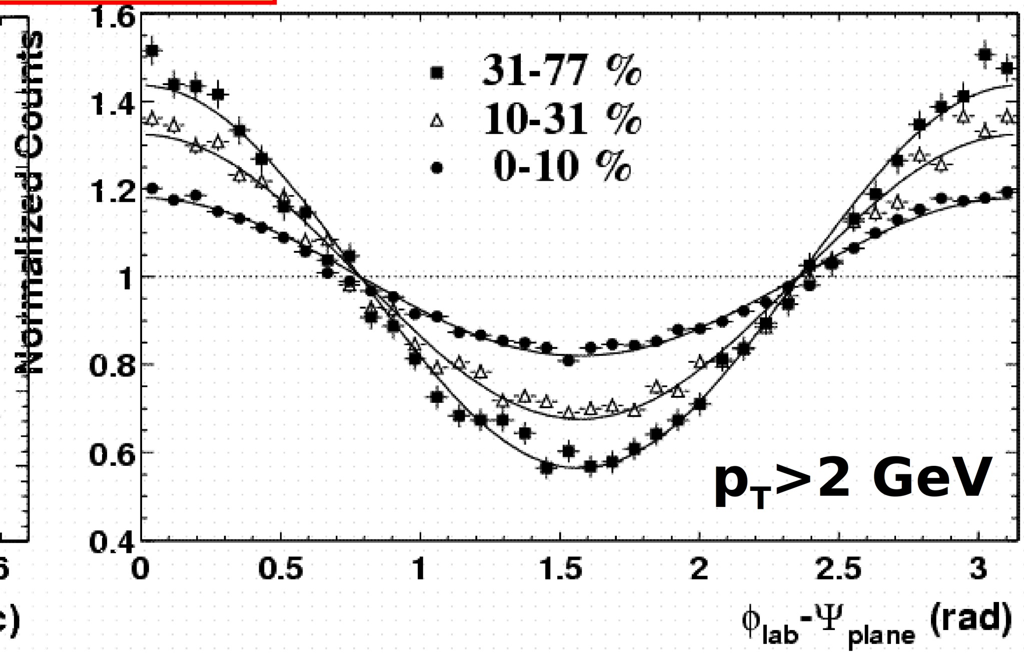
Transverse Elliptic Flow is a Barometric probe of sQGP Pressure in A+A

$V_2(p_T) = \langle \cos(2\phi) \rangle$

STAR PRL 2001

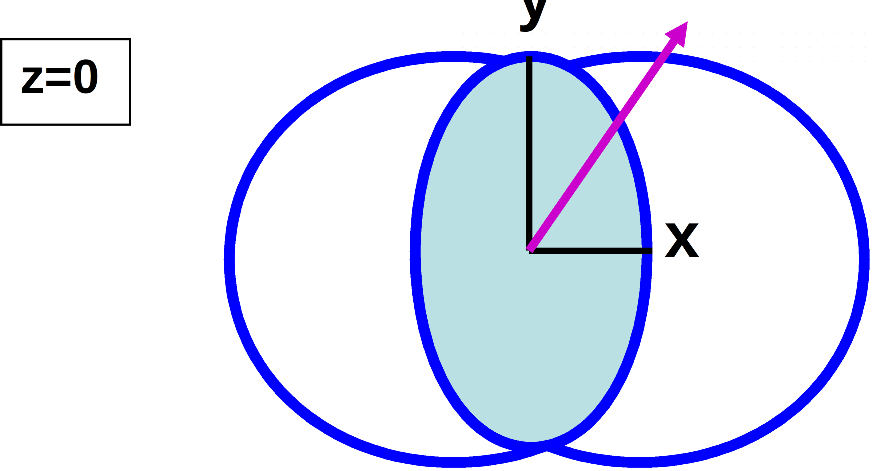
$dN^{ch}/d(\phi - \Phi_{reac})$





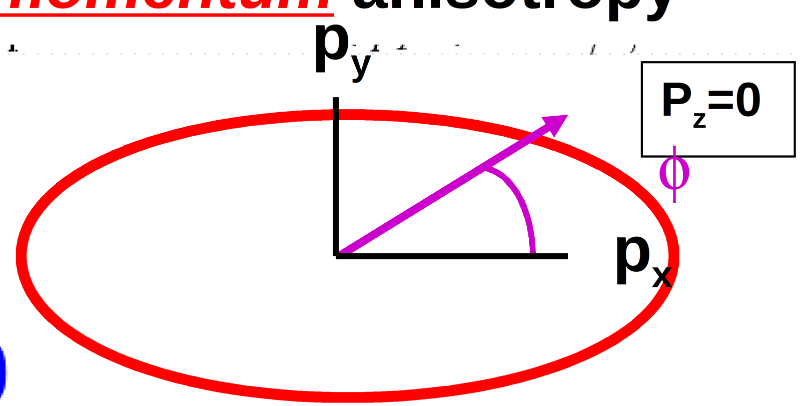
Initial *spatial* anisotropy

Final *momentum* anisotropy



$\Longrightarrow$

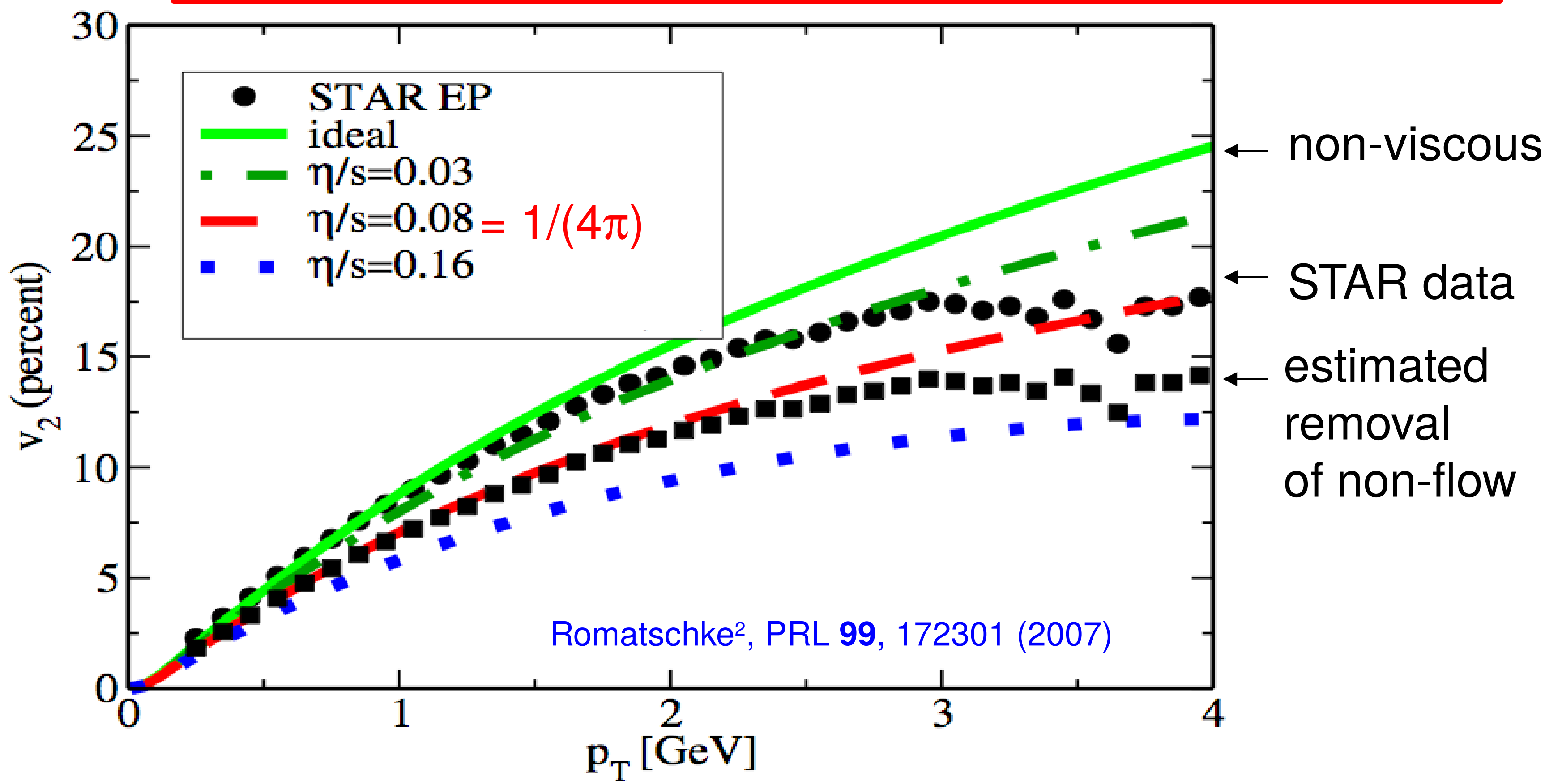
$$\partial_\mu T^{\mu\nu} = 0$$



Stoecker, Greiner 84, Ollitrault 92

Viscous Hydrodynamics Analysis of Elliptic Flow

Adapted From Art Poszkanzer T.Bonner Prize 2008 talk slide 26



Data: removing non-flow lowers v_2

Hydro: increasing viscosity lowers v_2

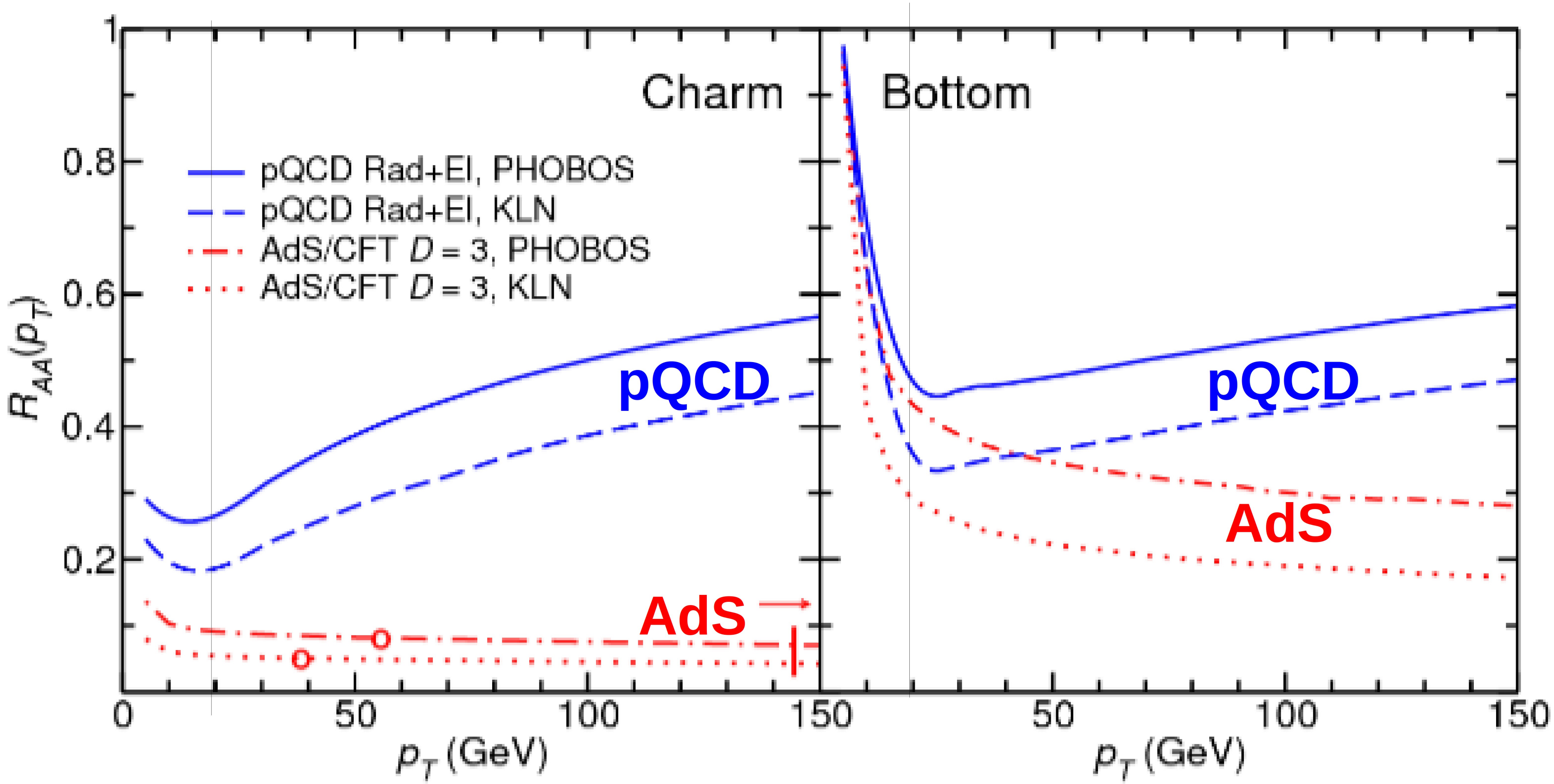
- Inferred η/s is at least 5 times smaller than any other known substance

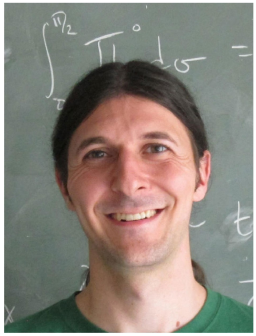
STAR, B.I. Abelev et al., Phys.Rev. C77 (2008) 054901

Non-photonic
Electron Quenching

Re ~ (Rc +Rb)/2

W. Horowitz, MG 2007
J. Noronha, G. Torrieri, MG 2010





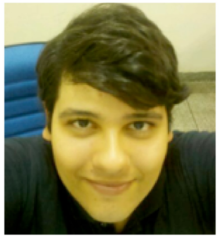


FIG. 1: (Color Online) $R^c_{AA}(p_T)$ and $R^b_{AA}(p_T)$ predicted for central Pb+Pb at LHC comparing AdS/CFT Eq. (1) and pQCD using the WHDG model [2

AdS solves the Heavy Quark Puzzle but by over quenching charm jets

$$\frac{dp_T}{dt} = -\mu_Q p_T = -\frac{\pi\sqrt{\lambda}(T^*)^2}{2M_Q} p_T$$

Also AdS fit requires too small t'Hooft coupling λ ~ 1 >> 1

Recent work A.Ficnar,S.Gubser,MG (2014) may help