Jet Tomo-graphy of wQGP via pQCD

Versus

Jet Dermo-graphy of sQGP via Holography

In A+A at RHIC and LHC

Miklos Gyulassy (Columbia University) 6/28/10 @ INT/UW

Tomo collabs: M. Plumer, M. Thoma, XN.Wang, P.Levai, I.Vitev, M.Djordjevic, A. Adil, W.Horowitz, S. Wicks, A. Buzzatti, A. Ficnar

Dermo collabs: W.Horowitz, J. Noronha, G. Torrieri, B. Betz, A. Ficnar
Part 1: Jet Tomography 1990-2004 (when life was easy)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10$ GeV) attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft $v2$ Hard RAA connection
       Jets in Turbulent Background Ensembles

Part 6: The fuzzy LHC crystal ball:
       Will 100 GeV Jets allow Tomography?
       Or will be confined to AdS Dermo-Holography?
Ideal **Volumetric** Tomography requires

1) Well controlled initial flux of *penetrating probes*

2) a *detailed dynamical theory* of probe energy loss and differential *scatt dN/dy d^2kT*

3) a cooperative *(not too wiggly, i.e. fluctuating)* patient

---

e.g, Cone-Beam Volumetric Tomography (CBVT)

Low dose 3D x-ray tomography in action at your nearest dentist
However only reduced **Surface Dermo-graphy** is possible if

1) Beam is **strongly absorbed** in the volume (*e.g. E+M from the sun*)

2) We need **detailed dynamical theory** of **surface or interface** physics between interior matter and the vacuum

3) a cooperative **(not too wiggly, i.e fluctuating)** patient

Cone-Beam Volumetric Tomography (CBVT)
Low dose 10 sec x-ray 3D tomograph

“BH” Information Loss

Only the Boundary “Corona” Can be imaged
In this case
Can *moderate* coupling extrapolations of pQCD lead to quantitative tomography of the QGP at RHIC and LHC?

Or

Is Radically new AdS/CFT Holographic Modeling required to "explain/model" Jet as well as Soft Bulk Observables in A+A?

J. Noronha, G. Torrieri, B. Betz, W. Horowitz, MG
Which paradigm can resolve the bottom quark puzzle? 
Will LHC also involve strong CGC preequilibrium suppression?
Gedanken pQCD Jet Tomography of A+A

Quark or Glue Jet probes:
\((\eta, \ p_T, \ \phi - \phi_{\text{reac}}, \ M_Q)_{\text{init}}\)

Hadron jet fragments:
\((\eta, \ p_T, \ \phi - \phi_{\text{reac}})_{\text{final}}\)

Measurements of hadronic quenching patterns provide information about QGP density evolution.

\[
\begin{align*}
\text{a) } & \Delta E^{\text{rad}} \propto \alpha_s^3 \int d\tau \tau \rho_{QGP}^2(\tau, \bar{r}(\tau)) \log\left(\frac{E_{Jet}}{\mu^2 L}\right) \\
\text{b) } & \Delta E^{\text{elas}} \propto \alpha_s^2 \int d\tau \rho_{QGP}^{2/3}(\tau, \bar{r}(\tau)) \log\left(\frac{E_{Jet}}{M(T)}\right) \\
\text{c) } & \Delta p_T^2 \propto \alpha_s^2 \int d\tau \rho_{QGP}(\tau, \bar{r}(\tau)) \log\left(\frac{E_{Jet}}{\mu}\right)
\end{align*}
\]

pQCD multiple collision theory in \textit{wQGP} (generalizing abelian QED plasmas)

Bj(82), GT(86), GP(90), GW(91-), BDMPS(97), ZLCPI(98), GLV (00), AMY(01), DGLV (03)

WHDG(05), ASW(05), MW(07), ZLCPI(08), AMY-HG(10), DGLV-BFW-MC(10) ...

Tomography can work only if QGP is not too opaque
pQCD tomography of A+A found close to expectations with $dE/dx \sim 1 \text{ GeV/fm}$

$DE(5 \text{ fm})/(E\sim15) \sim 1/3 \Rightarrow \text{marginal volumetric sensitivity}$

Fig. 1. The density of back-to-back jets at $y_1 = y_2 = 0$ in central U+U collisions at various CM energies per nucleon ($\sqrt{s}/2$) as a function of the jet transverse momentum $p_T$. Solid, dashed and dash-dotted show contributions from gg, gq, and qq jets, respectively.

Fig. 3. Dijet reduction factor for central A+A collisions at 100 A GeV as a function of $A$ for dijet energy $E = 30$. Curves are la-
High pT “hard” observables probe the “soft” sQGP

LHC buys: $>10^5$ higher flux of pp, pA, and pQCD calibrated penetrating hard probes of the sQGP
Light quark/gluon jet quenching pQCD theory passed many key RHIC exp. tests: A, Multiplicity, Ebeam, pT, flavor dependence

Opacity consistent with global Bulk entropy production (dN/dy~1000)

Suppression is very strong ($R_{AA}=0.2$!) and flat up to 20 GeV/c
Common suppression for $\pi^0$ and $\eta$; it is at partonic level
$\varepsilon > 15$ GeV/fm$^3$; $dN_g/dy > 1000$

Ivan Vitev, MG, PRL89 (02)
Centrality Dependence of High $p_T$

- Different centrality dependence of Au+Au vs D+Au
- Ruled out initial state shadowing/CGC effect at $y=0$ at RHIC
  $\Rightarrow$ initial parton flux well approx by $A \ast f_{a/A}(x,Q)$

T. Hemmick 6/18/03
"Return of the Jeti" in D+Au

Suppression of the back-to-back correlation in central Au+Au is a final-state effect

Near-side: \( p+p = d+Au = Au+Au \) \( \Delta \phi \) (radians)
Away-side: \( Au+Au \) monojet \( < < p+p = d+Au \) dijets

\( C_{BA}(\phi) \)

\( \frac{1}{N_{\text{Trigger}}} \frac{dN}{d(\Delta \phi)} \)

- \( d+Au \) FTPC-Au 0-20%
- \( p+p \) min. bias
- \( Au+Au \) Central

Mono-Jets
Early hint
That opacity
May be too high for volumetric Tomography

MGyulassy INT 6/28/10

P. Jacobs (STAR) 6/18/03
DGLV Theory of Mass M Quark Jet radiation + thermal glue dispersion
general n-th order in opacity induced gluon radiation

\[ x \frac{dN^{(n)}}{dx \, d^2k} = \frac{C_R \alpha_s}{\pi^2} \frac{1}{n!} \int \prod_{i=1}^{n} \left( \frac{d^2q_i}{\lambda_g(i)} \left[ \bar{v}_i^2(q_i) - \delta^2(q_i) \right] \right) \]
\[ \times \left( -2 \tilde{C}_{(1,\ldots,n)} \sum_{m=1}^{n} \tilde{B}_{(m+1,\ldots,n)}(m,\ldots,n) \right) \]
\[ \times \left[ \cos \left( \sum_{k=2}^{m} \varpi_{(k,\ldots,n)} \Delta z_k \right) - \cos \left( \sum_{k=1}^{m} \varpi_{(k,\ldots,n)} \Delta z_k \right) \right] \]

Formation Time
QCD LPM Effect

\[ \omega(m,\ldots,n) = \frac{(k - q_m - \cdots - q_n)^2}{2x \, E} \rightarrow \Omega(m,\ldots,n) \equiv \omega(m,\ldots,n) + \frac{m_g^2 + M^2 x^2}{2x \, E} \]

Current elements
“Dead Cones”

\[ \tilde{H} = \frac{k}{k^2 + m_g^2 + M^2 x^2}, \]
\[ \tilde{C}_{(i_1i_2,\ldots,i_m)} = \frac{(k - q_{i_1} - q_{i_2} - \cdots - q_{i_m})}{(k - q_{i_1} - q_{i_2} - \cdots - q_{i_m})^2 + m_g^2 + M^2 x^2} \]
\[ \tilde{B}_i = \tilde{H} - \tilde{C}_i, \]
\[ \tilde{B}_{(i_1i_2,\ldots,i_m)(j_1j_2,\ldots,j_n)} = \tilde{C}_{(i_1i_2,\ldots,i_m)} - \tilde{C}_{(j_1j_2,\ldots,j_n)}. \]
Formulas for $x, \bar{q}_b$ spectrum

\[ \frac{dP}{dxd\bar{q}_b} = \frac{2}{(2\pi)^2} \text{Re} \int d\bar{\tau} \exp(-i\bar{q}_b\bar{\tau}) \int_{z_2}^{z_f} dz_1 \int_{z_1}^{z_f} dz_2 \bar{g} \left\{ \Phi_f(\bar{\tau}, z_2)[K(\bar{\tau}, z_2, 0, z_1)
- K_v(\bar{\tau}, z_2|0, z_1)]\Phi_i(x\bar{\tau}, z_1) + [\Phi_f(\bar{\tau}, z_2) - 1]K_v(\bar{\tau}, z_2|0, z_1)[\Phi_i(x\bar{\tau}, z_1) - 1] \right\}
+ \frac{1}{(2\pi)^2} \int d\bar{\tau}d\bar{\tau}' \exp(-i\bar{q}_b\bar{\tau}) \psi_{a}^{bc*}(x, \bar{\tau}' - \bar{\tau}) \psi_{a}^{bc}(x, \bar{\tau}) [\Phi_f(\bar{\tau}, z_i) + \Phi_i(x\bar{\tau}, z_f) - 2]. \]

Here $z_{1,2}$ integrations comes only in the matter. For $L_f \gg L$ we have the picture

```
| z1 --| z2 |
```

scattering at $L_f \gg L$

\[ \frac{dP}{dxd\bar{q}_b} = \frac{1}{(2\pi)^2} \text{Re} \int d\bar{\tau}d\bar{\tau}' \exp(-i\bar{q}_b\bar{\tau}) \psi_{a}^{bc*}(x, \bar{\tau}' - \bar{\tau}) \psi_{a}^{bc}(x, \bar{\tau}) \left[ 2\Gamma_{bc\bar{a}}(\bar{\tau}', x\bar{\tau}) - \Gamma_{bb}(\bar{\tau}) - \Gamma_{a\bar{a}}(x\bar{\tau}) \right] \]

$\Gamma_h = 1 - \exp\left[-\frac{2}{x} \int_{-\infty}^{\infty} dz n(z)\right]$. For $q \to gq$ at $x \ll 1$ it gives the Kovchegov-Mueller


Also by S. Huot, C.Gale: 1006.2379 [hep-ph] in extended AMY-HG
Recent JET collab progress on numerical MC interpolation between $N=1$ and $N=\infty$

**DGLV & ASW**

$E=20$, $x=0.25$, $M_q=4.5$, $m_b=0$, $\mu=0.5$, $\lambda=1$, $L=5$

$n=0$ | $n=1$ | $n=1+2+3$ | $n=1+\ldots+5$ | ASW

See also:
Zakharov et al. LCPI
Hout et al. AMY-HG

Andej Ficnar
INT 6/25/10
Part 1: Jet Tomography 1990-2004 (when life was easy)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10 \text{ GeV})$ attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft $v2$ Hard RAA connection
   Jets in Turbulent Background Ensembles

Part 6: The fuzzy LHC crystal ball:
   Will 100 GeV Jets allow Tomography?
   Or will be confined to AdS Dermo-Holography?
DGLV/WHDG prediction falsified by PHENIX, STAR
Charm + Bottom → electron data in Au+Au 200AGeV RHIC

A bottom quark of 15 GeV does not stop in a 5 fm wQGP if data ok. Are there untried Standard Model pQCD mechanisms at work? Will data force us to abandon the wQGP paradigm?
Could *dynamic* HTL magnetic *scattering* + *dynamic geometry* help?

\[ |V(q)|^2 = \left[ \frac{\mu^2}{(q^2 + \mu^2)^2} \right]_{\text{stat}} \quad \leftrightarrow \quad \left[ \frac{\mu^2}{q^2(q^2 + \mu^2)} \right]_{\text{dyn}} \]

**Static GW Model**

**NonStatic HTL Model**

\[
\frac{\Delta E_{\text{dyn}}}{E} = \frac{C R \alpha_s}{\pi} \frac{L}{\lambda_{\text{dyn}}} \int dx \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{\mu^2}{q^2(q^2 + \mu^2)} \\
\times 2 \frac{k+q}{(k+q)^2 + \chi} \cdot \left( \frac{k+q}{(k+q)^2 + \chi} - \frac{k}{k^2 + \chi} \right) \left( 1 - \frac{\sin((k+q)^2 + \chi L)}{(k+q)^2 + \chi L} \right)
\]

\[
\chi \equiv M^2x^2 + m_g^2 \ (1-x)
\]

Heavy quark mass and thermal gluon mass effect

This was was answered by **A. Buzzatti** (LBL Jet Collab 6/19/10, INT 6/25/10)
Dynamic magnetic scattering enhances both light and heavy energy loss similarly.

But Bj expansion + diffuse surface geometry reduce energy loss of both similarly.

Two dynamical effects largely compensate each other and Do Not eliminate the heavy/light discrepancy with pQCD tomography.
At LHC, $p_T = 100$ GeV bottom and charm quarks may become penetrating Volumetric Probes if pQCD Tomography finally works at 10 times smaller wavelengths than at RHIC.

Figure 3: The charm (thick curves) and bottom (thin curves) quark radiative (solid line) and collisional (dashed line) energy loss for RHIC (left) at $\sqrt{s} = 200$ GeV and LHC (right) at $\sqrt{s} = 5.5$ TeV conditions for $L = 5$ fm, $m_c = 1.2$ GeV, $m_b = 4.5$ GeV. The dotted line shows the radiative energy loss for light quark. The calculations were performed with the running $\alpha_s$ and the $T$-dependent Debye mass from [40].
LHC with **identified** c and b Mesons up to 30 GeV will be critical in search for a clean heavy quark tomographic window on the QGP - **if it exists?**

*Heavy Ion Collisions at the LHC - Last Call for Predictions*

S. Wicks, MG (07)

---

**Figure 84:** $R_{AA}$ for observable products of heavy quark jets at RHIC (electrons - left) and two possible densities at the LHC (D and B mesons - right). There is considerable uncertainty in the perturbative production of c and b jets. This shows up in the results for electrons at RHIC in the large uncertainty band, ±0.1 or greater - as the ratio of c to b jets is very uncertain. However, the uncertainty in D and B meson $R_{AA}$ is small (approximately ±0.02) - the different slopes on the individual spectra have very little effect on the meson $R_{AA}$ results.
LHC Predictions

- Elastic still significant at LHC energies
- LHC: Power of power law of production more constant

PT>100 flavor independence predicted by pQCD

$v_2$ still too small at LHC?
Requiring a consistent account of both RAA(pi) and RAA(elec) As well as global entropy ~ dN/dy is prerequisite for Quantitative tomography within the wQGP/pQCD paradigm

\[
R_{AA} = (1 - \varepsilon^*)^n
\]

\[
\text{RAA (g)} \sim \left(1 - \frac{9}{4} \varepsilon^* \right)^n = \left(1 - \frac{9}{4} \left(1 - \text{RAA}^{1/4} (u) \right) \right)^4
\]

Glue Tomography is impossible if \( R_{AA} (u) = R_{AA} (c) < (5/9)^4 = 0.1 \)

Upper bound on any flavor q combined rad+el Energy loss fraction with Casimir g/q =9/4 assumed

\[
R_{AA} (g,E,L) > 0 \implies \varepsilon(q) = \Delta E(q)/E(q) < 4/9
\]

Otherwise Gluon Tomography demoted to Gluon Dermography (probing only the sQGP skin or “corona”)

Gluon Quenching Related to quark quenching
The bottom quark puzzle is disturbing because if it holds at LHC energy
Then all jet probes would be limited to Dermography of the sQGP

At RHIC $p_T < 20$
Bottom quarks would be the only Volumetric “Hadronic” Probes
of wQGP in pQCD

Secondary EM probes
$q \rightarrow q + \gamma + e + \mu$
Could give some bulk info

$g, u, d, s, c$ jets
Useful only to Probe the “surface”
Even at weak coupling $\alpha_s \sim 0.3$
Part 1: Jet Tomography 1990-2004 (when life was easy)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10 \text{ GeV})$ attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft v2 Hard RAA connection
   Jets in Turbulent Background Ensembles

Part 6: The fuzzy LHC crystal ball:
   Will 100 GeV Jets allow Tomography?
   Or will be confined to AdS Dermo-Holography?
Part 2: Another attack on pT~10 GeV pion Tomography : v2

Late week PHENIX posted new data v2(pT>9 GeV, Npart)

WHDG
W.Horowitz

Elliptic moment
Underpredicted

The SQGP
Is more of an Egg head than WHDG predicted
\[ V_2 \text{ favors } \Delta E(\text{static}) \propto L^3 \text{ inconsistent with pQCD} \]

\[ dE/dx \sim n(t) (t)^1 \]

\text{WHDG}

\[ dE/dx \sim n(t) (t)^2 \]

\text{AdS modified ASW}

\text{WHDG}

W. Horowitz

JR optics

V2 insensitive To geom

CGC vs GL

Andparticipant fluctuations

\text{MGyulassy INT 6/28/10}

JR=Dress,Feng,Jia: optical absorption model
$E^{1/3} \propto L_{\text{max}}$ is consistent with AdS holography

Light quark energy loss in strongly-coupled $N = 4$ supersymmetric Yang-Mills plasma.
Paul M. Chesler, Kristan Jensen, Andreas Karch, Laurence G. Yaffe, PRD79:125015,(2009.)

However “Light quarks lose the bulk of their energy in the latter stages of their trajectories … unlike heavy quarks”

Falling string model of light quark jet

\[ \Delta x_{\text{max}}(E) = \frac{0.526}{T} \left( \frac{E}{T\sqrt{\lambda}} \right)^{1/3}, \quad (4.62) \]

But $\frac{dE}{dL} \propto -T^4 L^2$

FIG. 7: The instantaneous energy loss rate, $dE/dt$, of a highly energetic quark, normalized by its initial energy $E_0$. Instead of decreasing with time, as might have been expected, the light quark energy loss rate actually increases. At times near the thermalization time, which for this particular example is $t_{\text{therm}} \sim 24/T$, the instantaneous energy loss rate grows like $dE/dt \sim 1/\sqrt{t_{\text{therm}} - t}$. 
Assume a scenario:
$T \approx T_c \pm \pm 10$ MeV Onion critical surface layer ansatz Shuryak, Liao 2008 has higher eccentricity than bulk geometry

Assume a nonperturbative Ansatz (e.g mag-monopole)
Green Onion ($T \sim T_c$)

Can easily fit PHENIX v2 data.

But how to distinguish from other elliptic-Lepricaun models??

Nonperturbative models must be able to predict
And correlate many different observables at once in a well defined math framework.

Contrast to AdS Holography paradigm that gives a powerful new calculus
To correlate many strongly coupled phenomenology
Part 1: Jet Tomography 1990-2004 (when life was simple)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10 \text{ GeV})$ attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft $v2$ Hard RAA connection

Part 6: The LHC crystal ball:
  Will 100 GeV Jets allow Tomography?
  Or will be confined to AdS Dermo-Holography?
3. **Jet Quenching in AdS/CFT**

\[
S = \frac{1}{2\kappa_5^2} \int d^5 x \left[ \sqrt{-G} \left( R + \frac{12}{L^2} \right) - \frac{2\kappa_5^2}{2\pi\alpha'} \int d^2 \sigma \sqrt{-g} \delta^5(x^\mu - X^\mu) \right]
\]

\[
R^3,1
\]

AdS$_5$–Schwarzschild

\[
\text{horizon}
\]

\[
\frac{dp_T}{dt} = -\mu Q p_T = -\frac{\pi \sqrt{\lambda (T^*)^2}}{2 M_Q} p_T,
\]

where $T^*$ is the temperature of the SYM plasma as fixed by the Hawking temperature of the dual D3 black brane.
Speed limit estimate for applicability of AdS drag

\[ \gamma < \gamma_{\text{crit}} = (1 + 2M_q/\lambda^{1/2} T)^2 \sim 4M_q^2/(\lambda T^2) \]

Gubser 07, Herzog et al 07

For \( \lambda = 30 \), \( M=4.5 \), \( T=0.2 \)

\[ \gamma_{\text{crit}} \sim 70 \]

String is tachyonic \( v > \text{local} \) speed of light below red world sheet horizon

As \( \gamma \to \gamma_{\text{crit}} \) apparent red horizon goes above D\& probe brane \( \Rightarrow \) string unstable
Bunching into a “pQCD band” vs a “AdS/CFT band” make this Double ratio of charm and bottom jet nuclear modification factors the ideal test of pQCD vs AdS/CFT gravity models of sQGP

\[ R_{cb}^{\text{AA}} = \frac{R_{cAA}(p_T)}{R_{bAA}(p_T)} \]
Part 1: Jet Tomography 1990-2004 (when life was easy)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10 \text{ GeV})$ attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft $v_2$ Hard RAA connection
          Jets in Turbulent Background Ensembles

Part 6: The fuzzy LHC crystal ball:
          Will 100 GeV Jets allow Tomography?
          Or will be confined to AdS Dermo-Holography?
AdS Holography Connects Thermo to Dissipation to Nonequilib dynamics

Noronha, Gyulassy, Torrieri, (2009),

With Phenomenological \( R^2 \propto \lambda_{GB} \sim 1/N_c \) + \( R^4 \propto \lambda^{-3/2} \) pertubations to \( R^1 (AdS_5) \)

\[
\frac{\eta}{s} = \frac{1}{4\pi} \left( 1 - 4\lambda_{GB} + 15 \frac{\zeta(3)}{\lambda^{3/2}} \right)
\]

\[
\frac{s}{s_{SB}} = \frac{3}{4} \left( 1 + \lambda_{GB} + \frac{15}{8} \frac{\zeta(3)}{\lambda^{3/2}} \right)
\]

Heavy quark energy loss

\[
\frac{dp}{dt} = -\frac{\sqrt{\lambda} \pi T^2}{2M_Q} \left( 1 + \frac{3}{2} \lambda_{GB} + \frac{15}{16} \frac{\zeta(3)}{\lambda^{3/2}} \right)
\]

* New result
J. Noronha

Main limitation is that assumed conformal invariance that does not hold \( T \sim T_c \)
We compute $R_{AA}^e$ via HQ Drag Model

\[
R_{AA}^Q(p_T, b) = \int_0^{2\pi} d\phi \int d^2 \vec{x}_\perp \frac{T_{AA}(\vec{x}_\perp, b)}{2\pi N_{bin}(b)} \\
\times \exp \left[ -n_Q(p_T)F_Q(\vec{x}_\perp, \phi) \right] \quad (14)
\]

where $N_{Bin}$ is the number of binary collisions and

\[
F_Q(\vec{x}_\perp, \phi) = \sqrt{\lambda} \frac{\pi}{2M_Q} \left( 1 + \frac{3}{2} \lambda_{GB} + \frac{15 \zeta(3)}{16 \lambda^{3/2}} \right) \\
\times \int_\tau^\infty d\tau T^2(\vec{l}, \tau) \theta(T(\vec{l}, \tau) - T_f) \quad (15)
\]
FIG. 1 (color online). Anisotropy (3) divided by (1), as a function of initial entropy (4) divided by (2). Shown are results from hydrodynamic simulations for $\sqrt{s} = 200$ GeV Au + Au.

We compute $v_2(\lambda t'\text{Hooft})$ at RHIC by fitting Luzum, Romatschke curves. For $v_2(\eta/s)$ for CGC and Glabuber IC geometries.
Unlike pQCD that predicts (P. Danielewicz, MG (85)) \( \eta/s \sim 1 \) for wQGP

Conformal Holography predicts (KSS (02)) \( \eta/s = 1/4\pi \) as seen in \( v_2 \) for sQGP

Remarkable robust correlation between Hard and Soft sQGP dynamics

Via a single \( \lambda \sim 30 \) t’Hooft parameter neglecting worldsheet fluc and string loop and GB deform!
5 Fold AA observables correlations with 2 (AdS+GB)/CFT couplings

J. Noronha, G. Torrieri, MG:0906.4099 [hep-ph]

(3) Heavy quark Jet quenching
(4) Initial Conditions
(1) Lattice $S/S_{SB} = 0.85 \pm 0.05$

5 $< \lambda < 30$
$|\lambda_{GB}| \leq 0.09$

Glauber

Heavy quark Jet induced collective flow

The Future

(2) Bulk Collective Flow

$R^e_{AA}(p_T = 5.5 \text{ GeV})$

(20–60%) PHENIX STAR

$\nu_2(p_T = 1 \text{ GeV}, \eta/s)$ via Luzum, Romatschke
PRC78 (08)
Part 1: Jet Tomography 1990-2004 (when life was easy)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10$ GeV) attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft $v2$ Hard RAA connection

Part 6: The fuzzy LHC crystal ball:
  Will 100 GeV Jets allow Tomography?
  Or will be confined to AdS Dermo-Holography?
sQGP Holography and Jet Finding
Jets and medium are inseparable
At strong coupling !!

Conventional Cone, kt , anti-kt, Gaussian filter, …

Are all **Doomed to fail** except for the occasional “Corona Jets” produced in the T< Tc “surface”

Holography and Jet Tomography do not commute

We have to accept that Jet are limited to **Dermo-graphy** except at much higher pT where pQCD should eventually apply
Strong coupling means that jet dynamics **amplifies** all initial state fluctuations.

Jets correlations are sensitive to distribution of "IC Ensemble" at $t \sim 0.5$ fm/c.

---

Order 1

Energy density
Hot spot fluctuations

From HIJING
Minijets + Soft

---

See papirus

---

MGyulassy INT 6/28/

MG, D.Rischke, B.Zhang NPA613 (1997) 397
Holography is inconsistent with hydro evolution on ensemble averages smooth IC!!!

Strong coupling i.e. perfect fluidity means that every member of the ensemble evolves hydrodynamically in a nonlinear way.

Ave vs Event Turbulent Minijet Initial Conditions $t=0.5$ fm/c

MG, D. Rischke, B. Zhang NPA613 (1997) 397
The jet opacity line integral (see slide 36) is sensitive to **EOS dependent** collective flow correlations due to hydro amplified IC fluctuations that differ event by event.

\[ R_{AA} = \int D[\rho] W[\rho] \times \]

\[ \exp \left[ -n_Q \mu_Q \int_0^{\infty} \nabla \rho(x_0 + v\tau, \tau) \, d\tau \right] \]

Hydro evolved IC density

MGyulassy INT 6/28/10
For a simple Bag EOS
Strong shells and voids
Evolve from
Initial turbulent IC

Final jet + medium
Correlations differ

Event by Event
Example: One HIJING event evolved with Bag model IC

Initial CF smoothed dET/dphidy

Perfect hydro can Amplify

Initial fluctuations

Leading to structures On top of radial and collective flow

Turbulent Evolution with Phase Transition

A hard jet coupled to this Nonlinear evolution Cannot be separated

Except for Jets on the corona

Bj PdV work
Barbara Betz  Example of Jet-Medium interactions at strong coupling

Jets in AdS/CFT

Weak Mach wakes

Diffusion Plume

Non-Mach correlations caused by Neck region

Tiny $r \sim 1/\pi T$
Scale amplified
Via hydro evolution

$\cos \phi_M = c_s / v_{jet}$
Hot Spots I

Can fluctuating initial condition explain the 2+3-particle correlations?

Takahashi et al., PRL 103, 242301 (2009)

R. Andrade et al., arxiv: 0912.0803

F. Grassi, Talk at the Glasma Workshop, BNL, May 2010
Part 1: Jet Tomography 1990-2004 (when life was easy)

Part 2: The Bottom Quark assault on the pQCD paradigm (2005- now)

Part 3: The $v_2(p_T \sim 10$ GeV) attack and hints of $L^3$ Dermo-graphy

Part 4: Jumping into the AdS Black Brane with Dermo-Holography

Part 5: The AdS Soft v2 Hard RAA connection
    Jets in Turbulent Background Ensembles

Part 6: The fuzzy LHC crystal ball:
    Will 100 GeV Jets allow Tomography?
    Or will be confined to AdS Dermo-Holography?
Challenges of Jet Tomography in A+A

1) Initial production may be suppressed by small-x (Shadowing / CGC Saturation)

2) $0 < t < 1 \text{ fm/c}$ strong TRANSIENT color field (GLASMA, Turbulence) distort info

3) pQCD vs AdS Quenching in the sQGP during $T_0 > T > T_c \ (1 < t < 3 \text{ fm/c})$

4) Propagation through the Conformal Anomaly/ Monopole $T \sim T_c \ (3-5 \text{ fm/c})$

5) Propagation though a Confined Viscous Hadronic Gas $\ (5-10 \text{ fm/c})$
At RHIC D+Au was the decisive Null Control exp that settled CGC vs QGP debate.

At LHC p+Pb will be even more important because small $x \sim 0.001$ some saturation/shadowing models predicts very strong initial state nuclear effects that will have to be deconvoluted to apply AA->jet tomography.
The CGC Challenge to Both Tomo and Dermo Graphy

Figure 2: Nuclear modification factors for $\pi^0$ production in p+Pb collisions, $R_{pPb}^{\pi^0}$, for collision energies $\sqrt{s_{NN}} = 8.8$ (left) and 6.2 TeV (right) and for rapidities $y_h = 2$, 4, and 6. For comparison, the red dashed line corresponds to the same quantity calculated in the $k_t$-factorization scheme.

How to untangle PQCD from BH from saturated fields?

$K_T$-Fact GLR prediction with NO FSI!! $(R_{pPb})^2 \sim 0.25$!!
Effect of Hadron FSI
$T < T_c = 170$ MeV ??

Or

Effect of initial GLASMA induce Flow near $T_0$ ?

PT averaged elliptic flow $v_2$ per geometric eccentricity systematics suggest

breakdown of perfect fluidity?
breakdown of even ideal fluidity?
On Nov 1, 2010

LHC scheduled to begin PbPb program

Our current RHIC picture of sQGP

Will likely drastically change

As strong IC shadowing/CGC, Pre-equilibrium transient GLASMA dynamics, Perfect fluidity $T>T_c$ of sQGP core and Demonic Fluidity of its HRG corona

Could lead to many new surprized