Questions and Lessons from the Work of John, PHENIX, and others

lesson [ˈlesən]
noun

1. that which one learns when one’s attempt to find the answer doesn’t succeed
Nuclear Matter Phase Diagram

G. Baym, Bielefeld Workshop on Quark Matter, 1983

- Early universe
- Heavy Ion Collisions (Central Region)
- Heavy Ion Collisions (Fragmentation Region)
- Supernovae
- Confined hadrons
- Deconfined quarks, gluons (QGP)
- Neutron stars

Temperature ~180 MeV

Baryon Density ~1/fm³

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to see ourselves as others see us"  

Robert Burns, *To A Louse*

Map of the HED Universe

- HEDP 2004 Task Force
- Quark Gluon Plasma!
- What simple, compelling evidence do we have?

![Map of the HED Universe](image)
Elliptic Flow = $v_2$ = momentum anisotropy, pressure gradients
– divide both axes by valence quark number

Sensitive to early time pressure gradients, Flow exhibits partonic DoF
Stunning data-only results (2)

\[ R_{AA} = \frac{\text{Yield}_{AA}}{\left\langle \text{N}_{\text{binary}} \right\rangle_{AA}} \]

\[ \text{Yield}_{pp} \]

QGP medium opaque to high \( p_T \) mesons (from jets), but not direct photons

\[ \text{PHENIX preliminary} \]

\[ \pi^0, \eta, \text{dir. photon} T_{\gamma}=221 \pm 19 \pm 19 \text{ MeV} \]

some theoretical work still required
(see arxiv:0810.3194)
Shadowing, Cronin, ...

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Understanding space-time

• John’s work (& mine) focused on measuring space-time
  – Q: Why?
  – A: Because we can ... (necessary, but not sufficient)
• Initial expectations (static calculations) for large/long-lived source to accompany large entropy change in EoS
• Subsequent (hydro-)dynamic calculations w/ 1st order phase transition also predicted long-lived source

Note that initial LQCD calculations were quenched => 1st order phase transition.
• Recent calculations w/ improved staggered fermion action on $N_\tau=8$ lattices
• Deconfinement transition in the range 185-195 MeV
Interference of electric field intensity (plane waves) from source:

- HBT reference is to Hanbury Brown and Twiss, who developed theory and performed first measurements of stellar radii
- First application to particle physics, Goldhaber, Goldhaber, Lee, Pais (GGLP).

\[
\frac{P(p_1,p_2)}{P(p_1)P(p_2)} = 1 + \left| \mathcal{K}(p_1 - p_2) \right|^2
\]

Gaussian source in \( x_i \) yields Gaussian correlation in conjugate variable \( q_i = p_{1i} - p_{2i} \)


PRL 120, 300 (1960)
1. Flow (dynamical correlations) reduce *visible source* at higher pair momenta
2. Outwards direction is extended by duration of emission
3. Ratio of out to side radius (Rout/Rside) indicative of emission duration (QGP)
Radii show smooth evolution from fixed-target to collider energies


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• Hydro models are 2 for 3:
  – tune for spectra
  – match flow
  – neglect space-time (most difficult & least sensitive)
Quantum Opacity, the RHIC Hanbury Brown–Twiss Puzzle, and the Chiral Phase Transition

John G. Cramer, Gerald A. Miller, Jackson M. S. Wu, and Jin-Hee Yoon

Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

(Received 27 August 2004; published 18 March 2005)

We present a relativistic quantum-mechanical treatment of opacity and refractive effects that allows reproduction of observables measured in two-pion Hanbury Brown–Twiss (HBT) interferometry and pion spectra at RHIC. The inferred emission duration is substantial. The results are consistent with the emission of pions from a system that has a restored chiral symmetry.

DOI: 10.1103/PhysRevLett.94.102302 PACS numbers: 25.75.-q

- Adopt hydro-inspired “blast-wave” source
- Optical potential for medium interaction
  - revisit plane wave assumption
  - assume chiral symmetry to guide form of potential
- Fit parameters for blast wave + potential
Quantum Opacity Model Results

• Lessons...don’t be afraid to:
  – generate a complete solution, even if it requires 10 parameters
  – revisit standard (plane-wave) assumptions
  – cross the blood-brain barrier that too often separates theorists and experimentalists
And what of chiral symmetry?

Subtracted chiral condensate exhibits transition in same range as deconfinement
• some calculations predict significantly lower chiral transition \[ \text{PRD 80, 014504 (2009)} \]
• but both fermion actions violate discrete chiral symmetry (recovered in cont.)

Calculations on \( N_T = 12 \) lattices underway
Calculations with DWF (preserves descr. chiral) just a petaFlop away

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• QGP spectral broadening vs. rescattering effects

New detectors for STAR & PHENIX will soon improve statistics and systematics
HBT Puzzle Solution (2)

- Recent breakthrough by Vredevoogd and Pratt
  1. Boost Invariant Longitudinal Flow
  2. Traceless stress energy tensor
  3. Stress energy tensor anisotropy independent of transverse coordinate
- Explains large Rside and $k_T$ dependence
- *If correct*, addresses large uncertainty in setting initial conditions of hydrodynamics
HBT Puzzle Solution in 1D

- Comparison to pion Radii
  - a series of 10% effects
    1. pre-equ. flow
    2. LQCD EoS
    3. viscosity
    4. improved wave fns.
      - also works for kaons
      - still only 2/3 (no flow)
      - working on 3/3 with Scott using vh2 code by Luzum & Romatschke
PHENIX HBT Tails

- Beyond Gaussian parameterizations -> rescattering or QGP?

**Pions**

**Kaons**

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PHENIX

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• John’s refusal to live/work within self-imposed, arbitrary boundaries has benefitted the field, science, and sets an example for the rest of us.
Backup LQCD Material

\[ U_{-\mu}(n + \mu + \nu) = e^{iga[-A_\mu(n) - a\partial_\nu A_\mu(n) + O(a^2)]} \quad \text{1st Taylor series} \]

\[ U_{\nu}(n + \mu) = e^{iga[A_\mu(n)]} \quad \text{2nd Taylor series} \]

\[ = e^{iga^2(\partial_\mu A_\nu - \partial_\nu A_\mu) - ig[A_\mu , A_\nu]} = e^{ia^2gF_{\mu\nu}} = 1 - \frac{a^4g^2}{2}(F_{\mu\nu}F_{\mu\nu} + O(a^2)) \]

\[ S = \sum_{n,\mu<\nu} Tr[F_{\mu\nu}F_{\mu\nu}] + \text{const.} \]

\[ \quad \longrightarrow \quad \frac{1}{4} \int_0^{1/T} d^3x \int_0^{1/T} Tr[F_{\mu\nu}F_{\mu\nu}] = S_{\text{gluon}} \]

\[ U_{\mu}(n) = e^{igaA_\mu(n)} \]
LQCD Analysis

- Apply thermalization cut, remove autocorrelations
- Construct Trace Anomaly (deviation from massless ideal gas)

\[
\frac{\epsilon - 3p}{T^4} = \frac{\Theta_F^{\mu\mu}(T)}{T^4} + \frac{\Theta_G^{\mu\mu}(T)}{T^4} = R_\beta(\beta)N_\tau^4\Delta\langle s \rangle \\
R_\beta(\beta) = T \frac{d\beta}{dT} = -a \frac{d\beta}{da}
\]

\[
\frac{\Theta_F^{\mu\mu}(T)}{T^4} = -R_\beta R_mN_\tau^4 \left(2\hat{m}_l\Delta\langle \bar{\psi}\psi \rangle_l + \hat{m}_s\Delta\langle \bar{\psi}\psi \rangle_s \right)
\]

\[
\frac{\Theta_G^{\mu\mu}(T)}{T^4} = R_\beta N_\tau^4 \left(\Delta\langle s_G \rangle - R_u \left[6\beta'_r\Delta\langle R \rangle + 4\beta'_{pq}\Delta\langle C \rangle + \frac{1}{4\beta}\Delta\langle Tr \left(2D_l^{-1} + D_s^{-1}\right)\frac{dM}{du_0} \rangle \right]\right)
\]

- Temperature Scale Setting

Heavy quark potential
\[
\gamma(2S-1S)
\]

A. Gray, et al, PRD, 72:094507, 2005


\[
\left( \frac{r^2}{r_0} \right) \frac{dV_{qq}(r)}{dr} = 1.65 \\
r_0 = 0.469(7)
\]
• trace anomaly 85% gluonic (+ fermion interactions)
• larger cutoff effects for p4 fermions from LCP $R_m$
\[ \Theta_{\mu\mu} \text{ reprise : Hydro Parametrization} \]

- physically constrains high-T region
- reasonably describes peak, low-T
- single function avoids fluctuations
- few parameters (easy to transfer)

\[
\left( 1 - \frac{1}{1 + e^{(T-c_1)/c_2}} \right) \times \left( \frac{d_2}{T^2} + \frac{d_4}{T^4} \right)
\]

<table>
<thead>
<tr>
<th>Data</th>
<th>(d_2) [GeV](^2)</th>
<th>(d_4) [GeV](^4)</th>
<th>(c_1) [GeV]</th>
<th>(c_2) [GeV]</th>
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</thead>
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<tr>
<td>p4</td>
<td>0.24(2)</td>
<td>0.0054(17)</td>
<td>0.2038(6)</td>
<td>0.0136(4)</td>
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<tr>
<td>p4-10 MeV</td>
<td>0.241(6)</td>
<td>0.0035(9)</td>
<td>0.1938(6)</td>
<td>0.01361(4)</td>
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<tr>
<td>HRG+p4</td>
<td>0.24(2)</td>
<td>0.0054(17)</td>
<td>0.2073(6)</td>
<td>0.0172(3)</td>
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<tr>
<td>asqtad</td>
<td>0.312(5)</td>
<td>0.00</td>
<td>0.2024(6)</td>
<td>0.0162(4)</td>
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<td>asqtad-10 MeV</td>
<td>0.293(6)</td>
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<td>0.01670(4)</td>
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<tr>
<td>HRG+asqtad</td>
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<td>0.00</td>
<td>0.2048(6)</td>
<td>0.0188(4)</td>
</tr>
</tbody>
</table>

- Three fits each action (p4, asqtad)
  1. lattice data (solid)
  2. lattice data and HRG from 100-130 MeV (double-dot)
  3. lattice-10 MeV shift to approx. chiral/continuum shifts (dash)

see also poster by P. Huovinen
1. ready for hydro: smooth approx. to HotQCD EoS w/HRG
2. able to propagate systematic variation through models
Results with VH2 (viscous 2D+1)

Freezeout surface at with different input EoS

\[ b = 0 \text{ fm.}, A = 197, R_0 = 6.4 \text{ fm.}, \eta/s = 0.08, T_f = 150 \text{ MeV} \]

- Beginning to propagate EOS thru Hydro
- Preparing to add cascade afterburner->spectra/flow/HBT

trouble with (discrete) fermions

- 1D Dirac Eq. \( \frac{\partial \psi}{\partial t} = -\frac{i}{2a} \gamma_5 [\psi(n+1) - \psi(n-1)] \) has \( E = \pm \frac{\sin(ka)}{a} \)
- degenerate fermion states \( (2^d n_f) \)

Wilson action lifts degenerate states, breaks chiral symmetry, not widely used in thermodynamics

- preserves a discrete chiral symmetry
- additional terms improve cutoff effects

Staggering Dirac spinor states along 4-corners thins degeneracy by 4

- all have Symanzik gauge improvements \( O(a^2) \)
- all *should* converge as \( a \to 0 \)

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