The End
...or is it just the beginning?
Outline of the summary talk

1. Motivation why we need to summarize this workshop.
2. Summarize the themes of the workshop.
3. Summarize the summary.
The BIG picture

For too long we have been trapped by lattice methods when dealing with non-perturbative field theory phenomena!
The Lattice has problems:

- Difficulties in dealing with chiral symm and the massless quark limit.
- It’s a challenge to introduce a chemical potential.
- Combining temperature and real time evolution.
- Formulation of SUSY theories.
- Dynamics in strongly coupled CFTs (finite size effects).

AdS/CFT to the rescue!
RHIC experiments require understanding of hot dense QCD:

\[ T \sim 170 \text{MeV} \]

\[ \mu_B \sim 30 \text{MeV} \]

(W. Zajc)
Data suggests good agreement with hydrodynamics with a small $\eta/s$ ratio (implies strong coupling):

(W. Zajc)
HOT topics

• Plowing of heavy/energetic objects through the plasma and their energy loss.

• Effect of temp./density on the meson spectrum/dispersion relations (phase transitions).

• Transport properties.

• Response to external E & B fields.
Plasma Plows

Energy density for $v=3/4$

(A. Yarom)

Quasi-Particle excitations.

Final Diffusion

Zero T Jets
Quasiparticle in Plasma
(A. Karch)

See also E. Iancu
Equation of Motion

\[
\begin{align*}
\gamma^2 M_\Omega^2 \dot{X}_r(t) + \int_0^t dt' \gamma G_R \left( \frac{t-t'}{\sqrt{\gamma}} \right) X_r(t') &= \xi_r(t) \\
\gamma M_\Omega^2 \dot{Y}_r(t) + \int_0^t dt' \gamma G_R \left( \frac{t-t'}{\sqrt{\gamma}} \right) Y_r(t') &= \xi_t(t)
\end{align*}
\]

Small fluctuations on top of \( X = vt \)

Large mass \( \Rightarrow \) low frequency approximation of \( G_R \)

\[
\sqrt{\gamma} G_R(\sqrt{\gamma} \omega) = -i \gamma \sqrt{\lambda \pi T^2 \omega} + \gamma^{3/2} \sqrt{\lambda} T \omega^2
\]

\[
\begin{align*}
\gamma^2 M_{\text{bin}} X_r(t) + \frac{\sqrt{\lambda} \pi T^2}{2} \gamma^2 \dot{X}_r(t') &= \xi_L(t) \\
\gamma M_{\text{kin}} \dot{Y}_r(t) + \frac{\sqrt{\lambda} \pi T^2}{2} \gamma Y_r(t') &= \xi_t(t)
\end{align*}
\]

The effective mass is \( v \) dependent!

\[
M_{\text{bin}} = M_\Omega^2 - \frac{\sqrt{\gamma} \lambda T}{2}
\]

(Same as HKKKY at \( v = 0 \))

Since these are small fluctuations:

\[
\frac{dP}{dt} = -\mu P + \xi \dot{x} + \xi
\]

\[
\gamma \ll \frac{M_\Omega^2}{\lambda T^2}
\]

(J. Casalderrey-Solana)

(G. Moore)

\[
\frac{\kappa}{(\delta M)^2} = \frac{\pi T}{N^2} 8.37
\]

(J. Erdmenger)
Mesons at finite $T$ and $\mu$

(T. Faulkner)

(J. Erdmenger)

(D. Mateos)
mu -T phase diagrams

(D. Mateos)

(O. Bergman)
Approaching a thermal state

\[ T^{00}(t, z) = \frac{\bar{\mu} (\delta(x^+) + \delta(x^-))}{2} - 2\bar{\mu}^2 \theta(x^+) \theta(x^-) \left(x^{+2} + x^{-2} - 4x^+ x^-\right) \]

(M. Natsuume)

\[ \text{speed of sound} = \sqrt{D_\eta / \tau_\pi} \]

\[ D_\eta := \eta / (T_s) \]

(P. Romatschke)
Now with E & B fields

(O. Bergman)

(S. Hartnoll)

See also J. Erdmenger
COOL stuff

• Attempts to construct the dual string describing the field theory.
• Integrability and anomalous dimensions of operators.
• Using holography to calculate entanglement entropies.
• Using 5D models to describe spectra/form factors of mesons and baryons.
• Gravity duals and Beyond the Standard Model physics.
String construction

- QCD string from a subcritical NS string.

  Holographic low energy closed string spectrum
  - Tachyon pole at \( \alpha'(k^2 + \mu^2)/2 = (D - 1)/8 \) in \( \mathcal{M}^+ \).
  - No massless graviton poles
  - Massless RR (5D) closed string states in \( \mathcal{M}^- \)
    
    \[
    S, \quad A_{\mu r}, \quad A_{\mu}
    \]
  - Planar diagram sum should resolve the IR issues connected to the tachyon and the RR massless states.

  (C. Thorn)

- The dual to N=4 SYM from a coset GS string formalism.

  PR theory for \( AdS_5 \times S^5 \) superstring

  fermionic generalization of "gWZW+ potential" theory for
  
  \[
  \frac{G}{H} = \frac{Sp(2,2)}{SU(3) \times SU(2)} \times \frac{Sp(4)}{SU(2) \times SU(2)}
  \]

  \[
  L = L_{gWZW}(g, A_+, A_-) + \mu^2 \text{Str}(g^{-1} T g T)
  + \text{Str} (\Psi_L T D_+ \Psi_L + \Psi_R T D_- \Psi_R)
  + \mu \text{Str} (g^{-1} \Psi_L g \Psi_R)
  \]

  direct sum of bosonic PR theories for \( AdS_5 \) and \( S^5 \)

  "glued together" by components of fermions

  \[
  L = L_{S^5}(g, A_+, A_-) + L_{AdS_5}(g, A_+, A_-)
  + \psi_L D_+ \psi_L + \psi_R D_+ \psi_R + \mu \text{ (interaction terms)}
  \]

  all gauge symmetries fixed; standard kin. terms (cf. GS action)

  UV finite as a quantum theory (Roiban, AT, to appear)

  (A. Tseytlin)
Integrability in N=4 SYM

(A. Belitsky)

Exploring the fine structure

Systematic expansion of the all-order Baxter in WKB series:

Upper part of the spectrum, e.g.,

\[ \gamma_{(2)}(N,n) = (\psi''(1) + 2\psi'(1))^2 \left( \ln \frac{q^{(0)} N^3}{\sqrt{3}} - 6\psi(1) \right) - \frac{2}{\pi} \psi^{(4)}(1) - 3\psi'(1)\psi''(1) + O(1/N) \]

Kruczenski '04
Kruczenski, Tseytlin '07

Spiky string for the highest trajectory:

Lower part of the spectrum (arbitrary L):

One-loop analysis suggested the expansion:

\[ \gamma_{(1)} = 2g^2 \ln N \left[ 1 - \ln 2 \frac{L}{\ln N} - \frac{\psi''(1)}{4 \ln N} \sum_{\ell=2} L^{\ell-2} (\delta^{(0)})^{\ell} + \ldots \right] \]

Freyhult, Rej, Staudacher '07
Roiban, Tseytlin '07

Systematic expansion, e.g.,

\[ \gamma(g) = \ldots + g^6 \ln N \left[ \frac{-15}{4} \pi^4 \left( -\frac{3}{4} \pi^2 \xi(3) - 21 \xi(5) \right) \frac{L}{\ln N} + \ldots \right] \]

Encodes fine structure

Agrees with a different formalism …

Q: What is string configuration interpolating between low and upper boundaries?
Entanglement Entropy

(A.Murugan)

\[ S_A(\ell) \]

boundary

bulk

\[ S_A^{(\text{disconn})} \]

\[ l_{\text{crit}} \quad l_{\text{max}} \quad 1 \]

\( \tilde{S} \) as a function of \( R_i \)

(A.Parnachev)
5D models of hadrons

(A.Pomarol)

See also A. Radyushkin’s talk on hadron form factors.

(T.Gherghetta)
Gravity duals work for physics beyond the SM

See also O. DeWolfe’s talk for a gravity dual with a metastable SUSY breaking vacuum.
Summarizing the summary

• AdS/CFT provides us with new tools for non-perturbative dynamics

• These tools may be useful in various physical systems:
  RHIC - perhaps getting just the universal is enough, although getting closer to QCD is desirable.

Beyond the standard model and the LHC.

FUTURE? Condensed matter systems.
Let’s thank the organizers for a great workshop!

D. Son, M. Stephanov, M. Strassler, & D. Teaney