Can we study real time dynamics of string theory?

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QFT Holography = Black Hole
For imaginary time, lattice simulation is powerful and probably the only practical tool in generic situation. (Enrico Rinaldi’s talk next week)
(Euclidean simulation is nice) but I want to know real time dynamics. Lattice gauge theory doesn’t work, does it?

(Joe Polchinski → MH, 2013)
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Challenge accepted
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Challenge accepted

That was (not a challenge but) a wish list :).

(Joe Polchinski → MH, 2015)
We should consider all possibilities, not necessarily lattice gauge theory.

- Quantum simulation? 10-20 minutes
- Classical Yang-Mills? 30-40 minutes
- Classical Yang-Mills + quantum effect? 0-5 minutes
- Or better ideas?

coffee break, or tonight before (3:00 am)
Quantum Simulation?
QFT \hspace{1cm} \text{Holography} \hspace{1cm} = \hspace{1cm} \text{Black Hole}

‘the other world’ \hspace{1cm} \text{Our world with gravity}
Let's make it in our world (almost) without gravity.

QFT = Holography

Black Hole

‘the other world’

Our world with gravity
Hamiltonian engineering on optical lattice

- A kind of problem-specific quantum simulation.
- Trap cold atoms by lasers and introduce appropriate interaction.
- Then Nature takes care of quantum time evolution.
- Perform measurement.
• Physical realization of a black hole.
• Physical realization of a black hole.

• Having actual physical one is (probably) more fun.
• Physical realization of a black hole.

• Having actual physical one is (probably) more fun.
• Physical realization of a black hole.

• Having actual physical one is (probably) more fun.

• What I cannot create, I do not understand.
Of course, Feynman did not literally mean to ‘create’.

‘What I cannot create, I do not understand.’

~ derive

‘Know how to solve every problem that has been solved.’
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But how can we ‘solve’ QFT and get actual numbers?
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‘Know how to solve every problem that has been solved.’

But how can we ‘solve’ QFT and get actual numbers?

Unless we create, we will not understand.

(Maybe.)
No wonder this circuit failed. It says, "Made in Japan."

What do you mean, Doc? All the best stuff is made in Japan.
No wonder this circuit failed. It says, "Made in Japan."

What do you mean, Doc? All the best stuff is made in Japan.

(Steven Spielberg, 1990)
I. Danshita (Kindai U.)

S. Nakajima  M. Tezuka  (Kyoto U.)

B. Sundborg  (Stockholm U.)

N. Wintergerst  (Niels Bohr Institute)
(1) ‘In Principle’ realization of SYK
   (Danshita, MH, Tezuka, 2016)

(2) More realistic realization of 3d Gross-Neveu
   (Danshita, MH, Nakajima, Sundborg, Tezuka, Wintergerst, at very elementary stage)
Complex SYK model

\[
\hat{H} = \frac{1}{(2N)^{3/2}} \sum_{ijkl} J_{ij,kl} \hat{c}_i^{\dagger} \hat{c}_j^{\dagger} \hat{c}_k \hat{c}_l
\]

\[
\{ \hat{c}_i, \hat{c}_j \} = \{ \hat{c}_i^{\dagger}, \hat{c}_j^{\dagger} \} = 0, \quad \{ \hat{c}_i^{\dagger}, \hat{c}_j \} = \delta_{ij}
\]

\[
J_{ij,kl} = -J_{ji,kl} = -J_{ij,lk}, \quad J_{ij,kl} = J_{kl,ij}^*
\]

Trap fermionic atoms in optical lattice and introduce appropriate interactions.
$J_{ij, kl} \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_k \hat{c}_l$
\[ J_{ij,kl} \hat{c}_i \hat{c}_j \hat{c}_k \hat{c}_l \]

molecule
\[ J_{ij, kl} \hat{c}_i^{\dagger} \hat{c}_j^{\dagger} \hat{c}_k \hat{c}_l \]

- **molecule**
- **photo-association**
  \[ g_{kl} \hat{m}^{\dagger} \hat{c}_k \hat{c}_l \]
- **photo-dissociation**
  \[ g_{ij} \hat{m} \hat{c}_i^{\dagger} \hat{c}_j^{\dagger} \]
spin-polarized fermions (no interaction)

Atomic site
- $E_{a,4}$
- $E_{a,3}$
- $E_{a,2}$
- $E_{a,1}$

Molecular site
- $E_{m,2}$
- $\Delta_{MB}$
- $E_{m,1} = E_m$

$\nu = 'detuning'$

Multiple molecular states $s$

$g_{kl} \hat{m} \hat{c}_k \hat{c}_l$

$g_{ij} \hat{m} \hat{c}_i \hat{c}_j$  \[ \frac{g_{ij} g_{kl}}{\nu} \hat{c}_i \hat{c}_j \hat{c}_k \hat{c}_l \]

$\sum_s \frac{g_{s,ij} g_{s,kl}}{\nu_s} \hat{c}_i \hat{c}_j \hat{c}_k \hat{c}_l \rightarrow J_{ij,kl} \hat{c}_i \hat{c}_j \hat{c}_k \hat{c}_l$

frosted glass $\rightarrow$ random $g_{ij}$
• In principle doable, but in practice, too many lasers are needed.

• There are several proposals by now.


• In principle doable, but in practice, too many lasers are needed.

• There are several proposals by now.

• Higher spin gravity may be a more tractable target.
SU(N) Gross-Neveu model

\[ \mathcal{L} = i \bar{\psi}_a \not{\partial} \psi_a + (\bar{\psi}_a \psi_a)^2 \]

SU(N) Hubbard model

\[ \hat{H} = -t \sum_{\langle i,j \rangle} \sum_{a=1}^{N} \left( \hat{c}^\dagger_{ia} \hat{c}_{ja} + \hat{c}^\dagger_{ja} \hat{c}_{ia} \right) + U \sum_{i} \left( \sum_{a=1}^{N} \hat{c}^\dagger_{ia} \hat{c}_{ia} \right)^2 \]

Hubbard on honeycomb lattice is believed to be 3d Gross-Neveu.
SU(N) Gross-Neveu model

\[ \mathcal{L} = i \bar{\psi}_a \gamma^i \gamma^5 \psi_a + (\bar{\psi}_a \gamma^5 \psi_a)^2 \]

SU(N) Hubbard model

\[ \hat{H} = -t \sum_{\langle i,j \rangle} \sum_{a=1}^{N} \left( \hat{c}^\dagger_{ia} \hat{c}_{ja} + \hat{c}^\dagger_{ja} \hat{c}_{ia} \right) + U \sum_i \left( \sum_{a=1}^{N} \hat{c}^\dagger_{ia} \hat{c}_{ia} \right)^2 \]

tunable by changing the depth of potential

Hubbard on honeycomb lattice is believed to be 3d Gross-Neveu.
\[
\hat{H} = -t \sum \sum_{\langle i,j \rangle}^{N} \left( \hat{c}_{ia}^\dagger \hat{c}_{ja} + \hat{c}_{ja}^\dagger \hat{c}_{ia} \right) + U \sum_{i} \left( \sum_{a=1}^{N} \hat{c}_{ia}^\dagger \hat{c}_{ia} \right)^2
\]

potential deep $\rightarrow$ less tunneling $\rightarrow$ small $t$

potential shallow $\rightarrow$ more tunneling $\rightarrow$ large $t$

potential deep $\rightarrow$ wave function more peaked $\rightarrow$ more overlap on the same site $\rightarrow$ large $U$

potential shallow $\rightarrow$ wave function spreads $\rightarrow$ less overlap on the same site $\rightarrow$ small $U$

$U/t$ is tunable
SU(2)

'half-filling': \(\#(\uparrow) = \#(\downarrow) = \#(\text{site})/2\)

- **large \(U/t\)**
  - anti-ferromagnet
  - spins cannot move

- **small \(U/t\)**
  - critical point
  - \(=\) Gross-Neveu
  - spins can move easily
'half-filling': \( (c_1) = \ldots = (c_N) = \#(\text{site})/2 \)
• SU(N) Hubbard Model is experimentally realized by now.
• Honeycomb optical lattice is also realized.

3d Gross-Neveu is within reach?
Isotopes of Ytterbium

<table>
<thead>
<tr>
<th>Nuclide symbol</th>
<th>Z/p</th>
<th>N/q</th>
<th>Isotopic mass (u)</th>
<th>Half-life</th>
<th>Decay mode(s)</th>
<th>Daughter isotopes</th>
<th>Nuclear spin and parity</th>
<th>Representative isotopic composition (mole fraction)</th>
<th>Range of natural variation (mole fraction)</th>
<th>Excitation energy</th>
<th>SU(6), SU(2), SU(4), SU(6), SU(8), SU(10) are doable with Strontium etc</th>
</tr>
</thead>
<tbody>
<tr>
<td>186Yb</td>
<td>70</td>
<td>78</td>
<td>147.967(4) AM</td>
<td>2509 ms</td>
<td>β⁺</td>
<td>186Tm</td>
<td>0⁺</td>
<td>186Tm (0⁺)</td>
<td>186Tm (0⁺)</td>
<td>7909 (2→0)</td>
<td>SU(6)</td>
</tr>
<tr>
<td>187Yb</td>
<td>70</td>
<td>79</td>
<td>148.9645 AM</td>
<td>0.722 s</td>
<td>β⁺</td>
<td>187Tm</td>
<td>(1/2-,3/2+)</td>
<td>187Tm (1/2-)</td>
<td>187Tm (1/2-)</td>
<td>18709 (2→0)</td>
<td>SU(6)</td>
</tr>
<tr>
<td>188Yb</td>
<td>70</td>
<td>80</td>
<td>149.9642(40) AM</td>
<td>7.09 ms</td>
<td>β⁻, 188Yb (1/2-), 188Yb (3/2-)</td>
<td>188Tm (1/2-)</td>
<td>188Tm (1/2-)</td>
<td>188Tm (1/2-)</td>
<td>18809 (2→0)</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>186mYb</td>
<td>70</td>
<td>79</td>
<td>150.9654(32) AM</td>
<td>1.65 s</td>
<td>β⁺, p (0.42%)</td>
<td>186Tm (1/2-)</td>
<td>186Tm (1/2-)</td>
<td>186Tm (1/2-)</td>
<td>110</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>187Yb</td>
<td>70</td>
<td>81</td>
<td>151.9650(32) AM</td>
<td>750(120) keV</td>
<td>β⁺, p (0.20%)</td>
<td>187Tm (1/2-)</td>
<td>187Tm (1/2-)</td>
<td>187Tm (1/2-)</td>
<td>750(120)</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>188Yb</td>
<td>70</td>
<td>82</td>
<td>152.9649(21) AM</td>
<td>2.67(7) μs</td>
<td>β⁻, 188Yb (1/2-), 188Yb (3/2-)</td>
<td>188Tm (1/2-)</td>
<td>188Tm (1/2-)</td>
<td>188Tm (1/2-)</td>
<td>90(2)</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>189Yb</td>
<td>70</td>
<td>83</td>
<td>153.9649(21) AM</td>
<td>240(1) μs</td>
<td>β⁻, 189Yb (1/2-), 189Yb (3/2-)</td>
<td>189Tm (1/2-)</td>
<td>189Tm (1/2-)</td>
<td>189Tm (1/2-)</td>
<td>240(1)</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>190Yb</td>
<td>70</td>
<td>84</td>
<td>154.9650(19) AM</td>
<td>0.409(2) s</td>
<td>α (92.8%), 190Yb (1/2-), 190Yb (3/2-)</td>
<td>190Tm (1/2-)</td>
<td>190Tm (1/2-)</td>
<td>190Tm (1/2-)</td>
<td>20</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>191Yb</td>
<td>70</td>
<td>85</td>
<td>154.9650(19) AM</td>
<td>1.75(13) s</td>
<td>α (99%), 191Yb (1/2-), 191Yb (3/2-)</td>
<td>191Tm (1/2-)</td>
<td>191Tm (1/2-)</td>
<td>191Tm (1/2-)</td>
<td>175(13)</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>192Yb</td>
<td>70</td>
<td>86</td>
<td>155.9650(19) AM</td>
<td>16.1(7) s</td>
<td>β⁻ (90%), α (10%), 192Yb (1/2-), 192Yb (3/2-)</td>
<td>192Tm (1/2-)</td>
<td>192Tm (1/2-)</td>
<td>192Tm (1/2-)</td>
<td>16.1(7)</td>
<td>SU(6)</td>
<td></td>
</tr>
<tr>
<td>193Yb</td>
<td>70</td>
<td>87</td>
<td>156.9650(19) AM</td>
<td>38.6(10) s</td>
<td>α (99.8%), 193Yb (1/2-), 193Yb (3/2-)</td>
<td>193Tm (1/2-)</td>
<td>193Tm (1/2-)</td>
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<td>38.6(10)</td>
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<tr>
<td>194Yb</td>
<td>70</td>
<td>88</td>
<td>157.9650(19) AM</td>
<td>1.49(13) min</td>
<td>α (99.8%), α (0.2%)</td>
<td>194Tm (1/2-)</td>
<td>194Tm (1/2-)</td>
<td>194Tm (1/2-)</td>
<td>1.49(13)</td>
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<td></td>
</tr>
<tr>
<td>195Yb</td>
<td>70</td>
<td>89</td>
<td>158.9650(2) AM</td>
<td>167(0) min</td>
<td>β⁻</td>
<td>195Tm (1/2-)</td>
<td>195Tm (1/2-)</td>
<td>195Tm (1/2-)</td>
<td>167(0)</td>
<td>SU(6)</td>
<td></td>
</tr>
</tbody>
</table>

stable, spin 5/2 → SU(6)

- SU(2), SU(4), SU(6), SU(8), SU(10) are doable with Strontium etc
Lattice gauge theory on optical lattice?

Cirac (Max Planck), Zoller (Innsbruck), Wiese (Bern), Reznik (Tel Aviv), ...

• (try to) construct Kogut-Susskind Hamiltonian

\[ \mu, \nu = x, y, z \]

Kogut-Susskind, 1974

• hard to implement matrix d.o.f.

• but let’s stay tuned.

\[ [E^\alpha_{\mu, \vec{x}}, U_{\nu, \vec{y}}] = \delta_{\mu \nu} \delta_{\vec{x} \vec{y}} \cdot \tau^\alpha U_{\nu, \vec{y}}, \]

\[ [E_{\mu, \vec{x}}, E_{\nu, \vec{y}}] = [U_{\mu, \vec{x}}, U_{\nu, \vec{y}}] = [U_{\mu, \vec{x}}, U^\dagger_{\nu, \vec{y}}] = 0. \]
• Quantum simulation?

• Classical Yang-Mills?

• Classical Yang-Mills + quantum effect?

• Or better ideas?

Aoki-MH-Iizuka, JHEP 2015
Gur Ari-MH-Shenker, JHEP 2016
Berkowitz-MH-Maltz, PRD 2016
MH-Romatschke, in preparation
• In AdS/CFT, weak and strong couplings are often very similar.

• D0, D1, D2: weak coupling $\sim$ high temperature;

  classical simulation can be useful.

• Studies of classical D0-brane matrix model suggested it is useful at least for thermalization and equilibrium physics.

  Asplund, Berenstein, Trancanelli,..., 2011—
D0-brane quantum mechanics

\[ S = \frac{N}{\lambda} \int_0^{\beta=1/T} dt \, Tr \left\{ \frac{1}{2} (D_t X_i)^2 - \frac{1}{4} [X_i, X_j]^2 \right\} \]

\[ + \frac{1}{2} \bar{\psi} D_t \psi - \frac{1}{2} \bar{\psi} \gamma^i [X_i, \psi] \] (dimensional reduction of 4d N=4 SYM)

effective dimensionless temperature \( T_{\text{eff}} = \lambda^{-1/3} T \)

\( (\lambda^{-1/2} T \text{ for D1}, \lambda^{-1} T \text{ for D2}) \)

high-\( T \) = weak coupling = stringy (large \( \alpha' \) correction)
\[ L = \frac{1}{2g_{YM}^2} \text{Tr} \left( \sum_i (D_t X^i)^2 + \frac{1}{2} \sum_{i \neq j} [X_i, X_j]^2 \right) \]

\[
\begin{cases}
\frac{d^2 X^i}{dt^2} - \sum_j [X^j, [X^i, X^j]] = 0 \\
\sum_i \left[ X^i, \frac{dX^i}{dt} \right] = 0 \quad (A=0 \text{ gauge})
\end{cases}
\]

discretize & solve it numerically.
black $p$-brane solution
(Horowitz-Strominger 1991)

\[ ds^2 = \alpha' \left\{ \frac{U^{\frac{7-p}{2}}}{g_{YM} \sqrt{d_p N}} \left[ - \left( 1 - \frac{U_0^{7-p}}{U^{7-p}} \right) dt^2 + \sum_{i=1}^{p} dy_i^2 \right] \right. \]

\[ \left. + \frac{g_{YM} \sqrt{d_p N}}{U^{\frac{7-p}{2}} \left( 1 - \frac{U_0^{7-p}}{U^{7-p}} \right)} dU^2 + g_{YM} \sqrt{d_p N} U^{\frac{p-3}{2}} d\Omega_{8-p}^2 \right\}, \]

\[ e^\phi = (2\pi)^{2-p} g_{YM}^2 \left( \frac{g_{YM} d_p N}{U^{7-p}} \right)^{\frac{3-p}{4}}, \quad d_p = 2^{7-2p} \pi^{\frac{9-3p}{2}} \Gamma \left( \frac{7-p}{2} \right), \]

\[ T_{D0} = \frac{7}{4\pi \sqrt{d_0} \lambda} U_0^{\frac{5}{2}} \]
black $p$-brane solution
(Horowitz-Strominger 1991)

$$ds^2 = \alpha' \left\{ \frac{U^{7-p}}{g_{YM} \sqrt{d_p N}} \left[ -\left(1 - \frac{U_0^{7-p}}{U^{7-p}}\right) dt^2 + \sum_{i=1}^{p} dy_i^2 \right] \geq 1 \text{ at } U = U_0 \right. \right.$$

for low-$T$

$$+ \frac{g_{YM} \sqrt{d_p N}}{U^{7-p} \left(1 - \frac{U_0^{7-p}}{U^{7-p}}\right)} dU^2 + \frac{g_{YM} \sqrt{d_p N} U^{p-3}}{2} d\Omega_{8-p}^2 \right\},$$

$$e^\phi = (2\pi)^{2-p} g_{YM}^2 \left(\frac{g_{YM} d_p N}{U^{7-p}}\right)^{\frac{3-p}{4}},$$

$$d_p = 2^{7-2p} \pi^{\frac{9-3p}{2}} \Gamma\left(\frac{7-p}{2}\right),$$

\[\ll 1 \text{ at 't Hooft large } N \text{ limit}\]

$$T_{D0} = \frac{7}{4\pi \sqrt{d_0} \lambda} U_0^{\frac{5}{2}}.$$
Matrix Model 101

• Flat directions at classical level \([X_M, X_{M'}] = 0\)

• Lifted by quantum effect (when fermion is negligible)
Matrix Model 101

- Flat directions at classical level \[ [X_M, X_{M'}] = 0 \]
- Lifted by quantum effect (when fermion is negligible)
Matrix Model 101

- Flat directions at classical level \([X_M, X_{M'}] = 0\)
- Lifted by quantum effect (when fermion is negligible)

Flat direction is measure zero already in the classical theory

(Gur Ari-MH-Shenker; Berkowitz-MH-Maltz)
(also, probably D. Berenstein knew it)
1 BH

2 BH’s

gas of D0’s
Let’s study this one.

1 BH

2 BH’s

gas of D0’s
Why no flat direction?

energy of $N$-th row & column $\sim \frac{1}{g^2} \sum_{i=1}^{d-1} \sum_{a=1}^{N-1} L^2 |X_{aN}^i|^2$

phase space suppression $\sum_{i=1}^{d-1} \sum_{a=1}^{N-1} |X_{aN}^i|^2 \lesssim g^2 E / L^2$

phase space volume at $L > L_0$ $\int_{L_0}^\infty \frac{L^{d-1}dL}{L^{2(d-1)(N-1)}} \sim \int_{L_0}^\infty \frac{dL}{L^{(d-1)(2N-3)}}$

Finite! (exception: $d=2$, $N=2$)
Lyapunov Exponent

\[ \delta \vec{x}(t) \sim \exp(\lambda_L t) \]
smallest size of the wave packet in phase space

\[ \sim \hbar \sim N^0 \]

uncertainty grows exponentially

maximum uncertainty

\[ \sim \sqrt{N} \]

size of the system
Exponential growth: $\exp(\lambda L t)$

$\lambda$: Lyapunov exponent

$\sim \sqrt{N}$

Graph: exponential growth $\sim \exp(\lambda t)$

$\lambda$: Lyapunov exponent

$N=6,8,12,16$
$\exp(\lambda_L t) \sim \sqrt{N}$

"scrambling time" $t_s = (\log N)/\lambda_L \sim \log N$
Lyapunov exponent @ large N

\[ \lambda_L \]

\[ 2\pi T \]

(Shenker-Stanford)

\[ 0.292 \left( \lambda_{\text{t Hooft}} T \right)^{1/4} \]

(Gur Ari-MH-Shenker)

(D1 and D2 are similar)

full quantum result?
1/N correction

(Stringy corrections push down the exponent)

\( \lambda_L \) vs. \( 1/N \)
Quasinormal mode

(LIGO Scientific Collaboration and Virgo Collaboration, 2016)
$X_M = 0, \dot{X}_M \neq 0$ \quad \text{thermalize} \quad \text{generic configuration}

\[
\sqrt{\frac{1}{N} \text{Tr} X^2} \quad \implies \quad \text{Re}(e^{i\nu t}) \sim \cos(\nu_R t)e^{-\nu_I t}
\]
\[ \text{Re}(e^{i\nu t}) \sim \cos(\nu_R t) e^{-\nu_I t} \]
\[ \text{Re}(e^{i\nu t}) \sim \cos(\nu_R t)e^{-\nu_I t} \]

\[ \sqrt{\frac{1}{N}\text{Tr}X^2} \]

Slowest decaying mode:

\[ \nu_R = 5.152(28) \times (\lambda T)^{1/4} \]

\[ \frac{\nu_L}{\nu_R} = 0.0717(14) \]
\[ \text{Re}(e^{i\nu t}) \sim \cos(\nu_R t) e^{-\nu_I t} \]

The figure shows a graph with the following parameters:

- Slowest decaying mode: \( \nu_R = 5.152(28) \times (\lambda T)^{1/4} \)
- Fast decaying modes: \( \nu_L = 0.0717(14) \)
- The graph indicates that the slowest mode is 'contaminated' by fast decaying modes.
Fourier modes

\[ \frac{1}{N} \text{Tr} X^2_M \]

kinetic energy

\[ \nu_R \]

MH-Romatschke
Black hole/black string topology change

MH-Romatschke

(From F. Pretorius’s webpage)
D1 wrapped on $S^1$

\[\text{gauge/gravity duality}\]

\[(1+1)\text{-d SYM on } S^1\]
T-duality

D1 wrapped on $S^1$

gauge/gravity duality

$(1+1)$-d SYM on $S^1$

D0 on T-dual $S^1$
T-duality

D1 wrapped on $S^1$

gauge/gravity duality

$(1+1)$-d SYM on $S^1$

D0 on T-dual $S^1$

gauge/gravity duality
Wilson line phase = location of D0

Distribution of Wilson line phase

- Uniform string
- Nonuniform string
- Black hole

(e.g. Aharony-Marsano-Minwalla-Wiseman)
Conjectured phase diagram

Conjectured phase diagram


\[ \beta = 1/T \]

- black hole
- 1st order
- 2nd order
- 3rd order
- uniform black string
- non-uniform black string
- Classical YM analysis here
• Strictly speaking, classical YM is not well-defined — UV catastrophe problem
• It still works at early time, as long as energy localized at IR.
Black String $\rightarrow$ Black Hole Topology Change

random initial condition $\xrightarrow{\text{thermalize}}$ uniform black string $\xrightarrow{\text{thermalize}}$ black hole

Quench $\left( E \rightarrow E \times c \right)$
Black String $\rightarrow$ Black Hole Topology Change

Gravitational Radiation (GR) is not enough.

(From F. Pretorius’s webpage)
Black String $\rightarrow$ Black Hole Topology Change

Quench \((E \rightarrow E \times c)\)

random initial condition $\rightarrow$ uniform black string $\rightarrow$ black hole

- Classical $\rightarrow$ Large $\alpha'$ correction
- Large N $\rightarrow$ No $g_s$ correction

GR is not enough.

Can $\alpha'$ alone assist the topology change?

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$T_{BS}, T_{BH}$ fixed ($E_{BS}/N^2, E_{BH}/N^2$ fixed)
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$\alpha'$ correction is enough.
\[ |W| = \left| \frac{1}{N} \sum e^{i\theta} \right| \]

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\[ T_{BS}, T_{BH} \text{ fixed (E}_{BS}/N^2, E_{BH}/N^2 \text{ fixed}) \]
Quasinormal mode can be estimated

\[ |W| = \left| \frac{1}{N} \sum e^{i\theta} \right| \]

\( T_{\text{BS}}, T_{\text{BH}} \) fixed \((E_{\text{BS}}/N^2, E_{\text{BH}}/N^2 \) fixed\)
Gravity side (strong coupling in YM)

\[ \nu_R \propto T, \quad \frac{\nu_I}{\nu_R} = \text{const} \]

@ Uniform black string phase

(0+1)-d

(1+1)-d YM

$2.904 \times (E/N^2)^{1/4}$

$\sim (E/N^2)^{1/4}$ can be shown analytically at low and high energy regions
• Quantum simulation?
• Classical Yang-Mills?
• Classical Yang-Mills + quantum effect?
• Or better ideas?

Buividovich-MH-Shaefer, in progress; EPJ Web Conf. 2018
Berkowitz-MH-Maltz, PRD 2016
Rinaldi-Berkowitz-MH-Maltz-Vranas, JHEP 2018
Can we confirm the expected quantum corrections?

Can we study black hole evaporation?

'Symmetric state approximation' supports this picture.

- SUSY assists the emission of D-branes.
- Effective potential acting on a probe brane can be estimated from Euclidean theory by Monte Carlo simulation.
Summary

- A lot of things to do.
- Let’s make a black hole in a lab!
- Classical YM is already interesting and useful.
- Quantum effects in the weak coupling region is within reach.
- ‘Hawking radiation’ at high temperature is within reach.
- Your ideas will be appreciated!