Quantum Gravity meets Stastical Physics II

Alex Belin - CERN

Oct 26^{th} @ Banff Intl Research Station

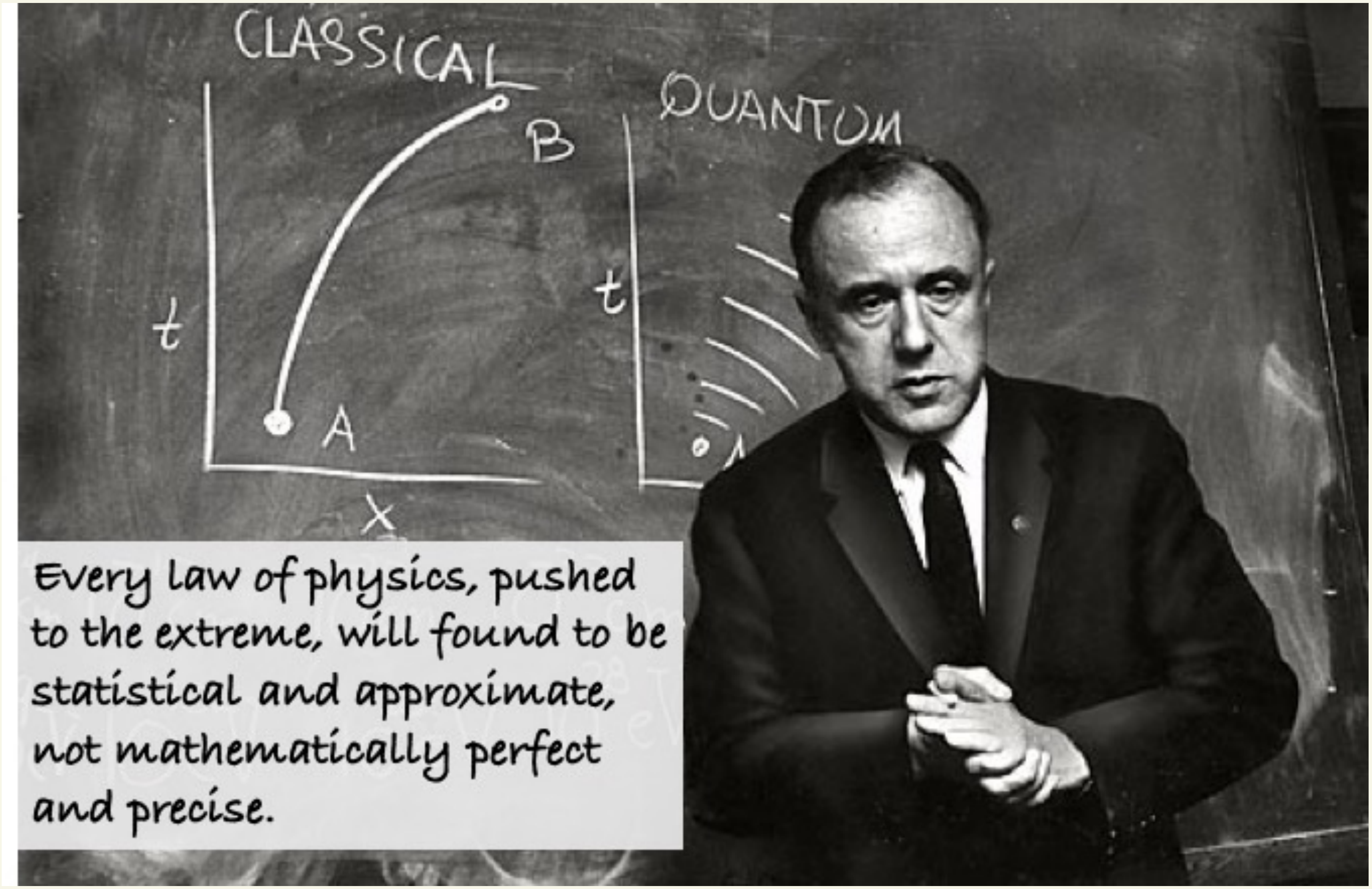
Based on:

2006.05499 w/ J. de Boer

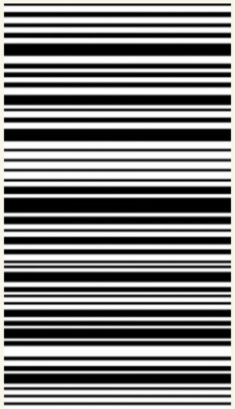
2110.xxxxx w/ J. de Boer, D. Liska

2111.xxxxx w/ J. de Boer, P. Nayak, J. Sonner

2111.xxxxx w/ T. Anous, J. de Boer, D. Liska



$\Rightarrow$ This seems like the right mindset to think about semi-classical gravity!



E_n

$R_{mn} = \langle E_m | O | E_n \rangle$

$$\begin{pmatrix}
0.78 & 0.2 & 0.85 & -0.24 & -0.98 & -0.74 & -0.46 & -0.86 & 0.52 & 0.29 & -0.25 & 1. & 0.29 & 0.9 & 0.93 & 0.66 & 0.95 & -0.34 & -0.01 & 0.07 \\
0.65 & 0.23 & -0.98 & 0.84 & -0.86 & -0.08 & -0.15 & 0.22 & -0.8 & 0.42 & -0.94 & -0.34 & -0.05 & -0.31 & -0.22 & -0.92 & 0.1 & -0.58 & -0.65 & -0.44 \\
-0.21 & -0.48 & -0.02 & 0.07 & -0.08 & -0.62 & 0.81 & 0.1 & -0.23 & -0.87 & -0.89 & 0.69 & 0.19 & -0.15 & -0.73 & -0.52 & -0.23 & 0.64 & -0.7 & -0.56 \\
0.94 & 0.1 & -0.78 & 0.5 & 1. & 0.98 & 0.03 & -0.06 & 0.66 & 0.75 & 0.11 & 0.85 & 0.94 & 0.19 & -0.78 & -0.38 & -0.41 & -0.84 & 0.91 & 0.04 \\
-0.78 & 0.67 & 0.58 & 0.58 & -0.3 & -0.16 & -0.75 & 0.84 & 0.48 & 0.67 & -0.31 & 0.05 & 0.43 & 0.36 & 0.26 & 0.61 & -0.53 & 0.12 & -0.56 & 0.53 \\
-0.32 & -0.49 & -0.29 & 0.35 & 0.18 & -0.55 & -0.75 & 0.2 & -0.01 & -0.14 & 0.58 & -0.21 & -0.88 & 0.69 & 0.46 & 0.82 & -0.26 & -0.77 & 0.92 & 0.6 \\
0.48 & 0.04 & -0.41 & 0.32 & -0.84 & -0.58 & 0.8 & 0.84 & -0.75 & -0.62 & -0.95 & -0.52 & 0.81 & 0.49 & -0.57 & 0.21 & 0.4 & 0.77 & -0.05 & -0.14 \\
0.29 & -0.04 & -0.65 & 0.64 & -0.68 & -0.06 & 0.3 & 0.88 & -0.78 & -0.72 & 0.77 & -0.57 & -0.54 & 0.35 & -0.68 & -0.86 & 0.48 & 0.6 & 0.76 & -0.86 \\
-0.67 & -0.53 & -0.23 & -0.47 & 0.21 & 0.65 & 0.29 & -0.65 & -0.66 & -0.76 & 0.16 & 0.79 & -0.21 & 0.83 & 0.46 & 0.65 & -0.38 & -0.37 & 0.5 & -0.86 \\
0.5 & -0.82 & 0.07 & 0.12 & 0.83 & 0.12 & -0.03 & -0.78 & 0.24 & -0.16 & 0.36 & -0.76 & 0.95 & -0.05 & 0.71 & -0.38 & 0.77 & 0.92 & 0.57 & 0.67 \\
0.08 & 0.14 & 0.37 & 0.64 & -0.82 & 0.51 & 0.78 & -0.81 & -0.85 & 0.46 & -0.97 & -0.13 & 0.48 & 0.29 & 0. & 0.9 & -0.91 & -0.56 & -0.42 & 0.26 \\
-0.96 & 0.9 & -0.47 & 0.01 & -0.94 & -0.52 & -0.77 & -0.62 & 0.62 & -0.14 & 0.98 & 0.05 & -0.3 & -0.88 & -0.01 & -0.69 & -0.24 & -0.7 & -0.39 & -0.57 \\
0.82 & -0.18 & 0.58 & -0.83 & -0.34 & -0.89 & -0.81 & 0.07 & 0.54 & -0.27 & -0.23 & -0.76 & -0.84 & -0.49 & 0.11 & 0.41 & -0.37 & -0.24 & -0.31 & 0.99 \\
-0.66 & 0.69 & -0.08 & 0.16 & 0.98 & 0.75 & -0.94 & 0.27 & 0.41 & -0.99 & -0.27 & 0.36 & -0.59 & 0.8 & 0.43 & -0.63 & -0.4 & -0.57 & -0.14 & 0.07 \\
-0.12 & -0.51 & -0.17 & 0.61 & 0.87 & 0.74 & 0.35 & -0.48 & -0.42 & 0. & -0.86 & -0.47 & -0.53 & -0.99 & -0.37 & -0.16 & 0.58 & -0.95 & -0.82 & 0.8 \\
0.56 & -0.66 & -0.99 & -0.66 & 0.57 & -0.18 & 0.92 & 0.14 & -0.27 & 0.73 & -0.36 & -0.45 & 0.84 & -0.27 & -0.46 & -0.75 & 0.62 & -0.89 & 0.39 & 0.14 \\
0.07 & 0.04 & 0.98 & -0.43 & -0.73 & 0.97 & 0.56 & 0.19 & 0.63 & -0.24 & 0.22 & 0.63 & -0.75 & 0.05 & 0.34 & 0.6 & -0.04 & -0.15 & 0.72 & 0.42 \\
-0.45 & -0.9 & 0.84 & -0.09 & 0.8 & 0.78 & 0.72 & 0.94 & 0.15 & -0.46 & 0.64 & -0.34 & -0.79 & 1. & -0.47 & 0.53 & -0.38 & -0.81 & 0.69 & 0.89 \\
-0.54 & -0.83 & -0.57 & 0.71 & 0.23 & -0.15 & -0.85 & -0.93 & -0.7 & 0.43 & -0.98 & 0.76 & -0.95 & 0.06 & -0.35 & 0.99 & 0.91 & -0.19 & -0.29 & 0.76 \\
-0.78 & -0.86 & 0.05 & -0.69 & 0. & -0.98 & 0.35 & 0.12 & -0.67 & 0.38 & -0.69 & 0.36 & -0.82 & -0.34 & -0.79 & 0.73 & 0.07 & 0.99 & -0.07 & -0.69
\end{pmatrix}$$

Microscopics

E_n $\quad$ $R_{mn} = \langle E_m | O | E_n \rangle$

0.78	0.2	0.85	-0.24	-0.98	-0.74	-0.46	-0.86	0.52	0.29	-0.25	1.	0.29	0.9	0.93	0.66	0.95	-0.34	-0.01	0.07
0.65	0.23	-0.98	0.84	-0.86	-0.08	-0.15	0.22	-0.8	0.42	-0.94	-0.34	-0.05	-0.31	-0.22	-0.92	0.1	-0.58	-0.65	-0.44
-0.21	-0.48	-0.02	0.07	-0.08	-0.62	0.81	0.1	-0.23	-0.87	-0.89	0.69	0.19	-0.15	-0.73	-0.52	-0.23	0.64	-0.7	-0.56
0.94	0.1	-0.78	0.5	1.	0.98	0.03	-0.06	0.66	0.75	0.11	0.85	0.94	0.19	-0.78	-0.38	-0.41	-0.84	0.91	0.04
-0.78	0.67	0.58	0.58	-0.3	-0.16	-0.75	0.84	0.48	0.67	-0.31	0.05	0.43	0.36	0.26	0.61	-0.53	0.12	-0.56	0.53
-0.32	-0.49	-0.29	0.35	0.18	-0.55	-0.75	0.2	-0.01	-0.14	0.58	-0.21	-0.88	0.69	0.46	0.82	-0.26	-0.77	0.92	0.6
0.48	0.04	-0.41	0.32	-0.84	-0.58	0.8	0.84	-0.75	-0.62	-0.95	-0.52	0.81	0.49	-0.57	0.21	0.4	0.77	-0.05	-0.14
0.29	-0.04	-0.65	0.64	-0.68	-0.06	0.3	0.88	-0.78	-0.72	0.77	-0.57	-0.54	0.35	-0.68	-0.86	0.48	0.6	0.76	-0.86
-0.67	-0.53	-0.23	-0.47	0.21	0.65	0.29	-0.65	-0.66	-0.76	0.16	0.79	-0.21	0.83	0.46	0.65	-0.38	-0.37	0.5	-0.86
0.5	-0.82	0.07	0.12	0.83	0.12	-0.03	-0.78	0.24	-0.16	0.36	-0.76	0.95	-0.05	0.71	-0.38	0.77	0.92	0.57	0.67
0.08	0.14	0.37	0.64	-0.82	0.51	0.78	-0.81	-0.85	0.46	-0.97	-0.13	0.48	0.29	0.	0.9	-0.91	-0.56	-0.42	0.26
-0.96	0.9	-0.47	0.01	-0.94	-0.52	-0.77	-0.62	0.62	-0.14	0.98	0.05	-0.3	-0.88	-0.01	-0.69	-0.24	-0.7	-0.39	-0.57
0.82	-0.18	0.58	-0.83	-0.34	-0.89	-0.81	0.07	0.54	-0.27	-0.23	-0.76	-0.84	-0.49	0.11	0.41	-0.37	-0.24	-0.31	0.99
-0.66	0.69	-0.08	0.16	0.98	0.75	-0.94	0.27	0.41	-0.99	-0.27	0.36	-0.59	0.8	0.43	-0.63	-0.4	-0.57	-0.14	0.07
-0.12	-0.51	-0.17	0.61	0.87	0.74	0.35	-0.48	-0.42	0.	-0.86	-0.47	-0.53	-0.99	-0.37	-0.16	0.58	-0.95	-0.82	0.8
0.56	-0.66	-0.99	-0.66	0.57	-0.18	0.92	0.14	-0.27	0.73	-0.36	-0.45	0.84	-0.27	-0.46	-0.75	0.62	-0.89	0.39	0.14
0.07	0.04	0.98	-0.43	-0.73	0.97	0.56	0.19	0.63	-0.24	0.22	0.63	-0.75	0.05	0.34	0.6	-0.04	-0.15	0.72	0.42
-0.45	-0.9	0.84	-0.09	0.8	0.78	0.72	0.94	0.15	-0.46	0.64	-0.34	-0.79	1.	-0.47	0.53	-0.38	-0.81	0.69	0.89
-0.54	-0.83	-0.57	0.71	0.23	-0.15	-0.85	-0.93	-0.7	0.43	-0.98	0.76	-0.95	0.06	-0.35	0.99	0.91	-0.19	-0.29	0.76
-0.78	-0.86	0.05	-0.69	0.	-0.98	0.35	0.12	-0.67	0.38	-0.69	0.36	-0.82	-0.34	-0.79	0.73	0.07	0.99	-0.07	-0.69

Microscopics

Semi-classical gravity

=

The thy of the stat. distribution of

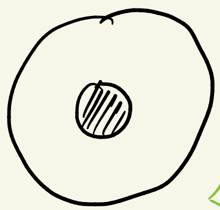
$\{E_n, R_{mn}\}$

E_n

$R_{mn} = \langle E_m | O | E_n \rangle$

0.78	0.2	0.85	-0.24	-0.98	-0.74	-0.46	-0.86	0.52	0.29	-0.25	1.	0.29	0.9	0.93	0.66	0.95	-0.34	-0.01	0.07
0.65	0.23	-0.98	0.84	-0.86	-0.08	-0.15	0.22	-0.8	0.42	-0.94	-0.34	-0.05	-0.31	-0.22	-0.92	0.1	-0.58	-0.65	-0.44
-0.21	-0.48	-0.02	0.07	-0.08	-0.62	0.81	0.1	-0.23	-0.87	-0.89	0.69	0.19	-0.15	-0.73	-0.52	-0.23	0.64	-0.7	-0.56
0.94	0.1	-0.78	0.5	1.	0.98	0.03	-0.06	0.66	0.75	0.11	0.85	0.94	0.19	-0.78	-0.38	-0.41	-0.84	0.91	0.04
-0.78	0.67	0.58	0.58	-0.3	-0.16	-0.75	0.84	0.48	0.67	-0.31	0.05	0.43	0.36	0.26	0.61	-0.53	0.12	-0.56	0.53
-0.32	-0.49	-0.29	0.35	0.18	-0.55	-0.75	0.2	-0.01	-0.14	0.58	-0.21	-0.88	0.69	0.46	0.82	-0.26	-0.77	0.92	0.6
0.48	0.04	-0.41	0.32	-0.84	-0.58	0.8	0.84	-0.75	-0.62	-0.95	-0.52	0.81	0.49	-0.57	0.21	0.4	0.77	-0.05	-0.14
0.29	-0.04	-0.65	0.64	-0.68	-0.06	0.3	0.88	-0.78	-0.72	0.77	-0.57	-0.54	0.35	-0.68	-0.86	0.48	0.6	0.76	-0.86
-0.67	-0.53	-0.23	-0.47	0.21	0.65	0.29	-0.65	-0.66	-0.76	0.16	0.79	-0.21	0.83	0.46	0.65	-0.38	-0.37	0.5	-0.86
0.5	-0.82	0.07	0.12	0.83	0.12	-0.03	-0.78	0.24	-0.16	0.36	-0.76	0.95	-0.05	0.71	-0.38	0.77	0.92	0.57	0.67
0.08	0.14	0.37	0.64	-0.82	0.51	0.78	-0.81	-0.85	0.46	-0.97	-0.13	0.48	0.29	0.	0.9	-0.91	-0.56	-0.42	0.26
-0.96	0.9	-0.47	0.01	-0.94	-0.52	-0.77	-0.62	0.62	-0.14	0.98	0.05	-0.3	-0.88	-0.01	-0.69	-0.24	-0.7	-0.39	-0.57
0.82	-0.18	0.58	-0.83	-0.34	-0.89	-0.81	0.07	0.54	-0.27	-0.23	-0.76	-0.84	-0.49	0.11	0.41	-0.37	-0.24	-0.31	0.99
-0.66	0.69	-0.08	0.16	0.98	0.75	-0.94	0.27	0.41	-0.99	-0.27	0.36	-0.59	0.8	0.43	-0.63	-0.4	-0.57	-0.14	0.07
-0.12	-0.51	-0.17	0.61	0.87	0.74	0.35	-0.48	-0.42	0.	-0.86	-0.47	-0.53	-0.99	-0.37	-0.16	0.58	-0.95	-0.82	0.8
0.56	-0.66	-0.99	-0.66	0.57	-0.18	0.92	0.14	-0.27	0.73	-0.36	-0.45	0.84	-0.27	-0.46	-0.75	0.62	-0.89	0.39	0.14
0.07	0.04	0.98	-0.43	-0.73	0.97	0.56	0.19	0.63	-0.24	0.22	0.63	-0.75	0.05	0.34	0.6	-0.04	-0.15	0.72	0.42
-0.45	-0.9	0.84	-0.09	0.8	0.78	0.72	0.94	0.15	-0.46	0.64	-0.34	-0.79	1.	-0.47	0.53	-0.38	-0.81	0.69	0.89
-0.54	-0.83	-0.57	0.71	0.23	-0.15	-0.85	-0.93	-0.7	0.43	-0.98	0.76	-0.95	0.06	-0.35	0.99	0.91	-0.19	-0.29	0.76
-0.78	-0.86	0.05	-0.69	0.	-0.98	0.35	0.12	-0.67	0.38	-0.69	0.36	-0.82	-0.34	-0.79	0.73	0.07	0.99	-0.07	-0.69

Microscopics



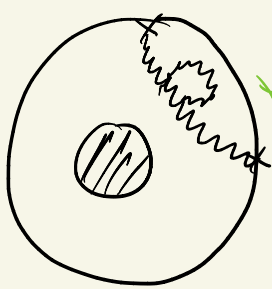
$S = \frac{A}{4G_N}$

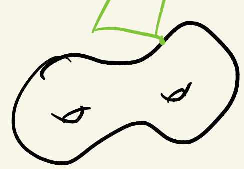
Semi-classical gravity

=

The thy of the stat. distribution of

$\{E_n, R_{mn}\}$

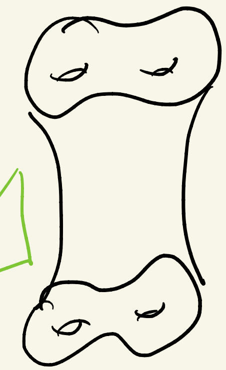


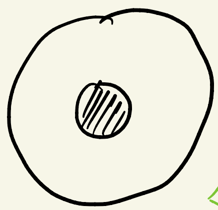


$$\left(\begin{array}{rrrrrrrrrrrrrrrrrrrr}
0.78 & 0.2 & 0.85 & -0.24 & -0.98 & -0.74 & -0.46 & -0.86 & 0.52 & 0.29 & -0.25 & 1. & 0.29 & 0.9 & 0.93 & 0.66 & 0.95 & -0.34 & -0.01 & 0.07 \\
0.65 & 0.23 & -0.98 & 0.84 & -0.86 & -0.08 & -0.15 & 0.22 & -0.8 & 0.42 & -0.94 & -0.34 & -0.05 & -0.31 & -0.22 & -0.92 & 0.1 & -0.58 & -0.65 & -0.44 \\
-0.21 & -0.48 & -0.02 & 0.07 & -0.08 & -0.62 & 0.81 & 0.1 & -0.23 & -0.87 & -0.89 & 0.69 & 0.19 & -0.15 & -0.73 & -0.52 & -0.23 & 0.64 & -0.7 & -0.56 \\
0.94 & 0.1 & -0.78 & 0.5 & 1. & 0.98 & 0.03 & -0.06 & 0.66 & 0.75 & 0.11 & 0.85 & 0.94 & 0.19 & -0.78 & -0.38 & -0.41 & -0.84 & 0.91 & 0.04 \\
-0.78 & 0.67 & 0.58 & 0.58 & -0.3 & -0.16 & -0.75 & 0.84 & 0.48 & 0.67 & -0.31 & 0.05 & 0.43 & 0.36 & 0.26 & 0.61 & -0.53 & 0.12 & -0.56 & 0.53 \\
-0.32 & -0.49 & -0.29 & 0.35 & 0.18 & -0.55 & -0.75 & 0.2 & -0.01 & -0.14 & 0.58 & -0.21 & -0.88 & 0.69 & 0.46 & 0.82 & -0.26 & -0.77 & 0.92 & 0.6 \\
0.48 & 0.04 & -0.41 & 0.32 & -0.84 & -0.58 & 0.8 & 0.84 & -0.75 & -0.62 & -0.95 & -0.52 & 0.81 & 0.49 & -0.57 & 0.21 & 0.4 & 0.77 & -0.05 & -0.14 \\
0.29 & -0.04 & -0.65 & 0.64 & -0.68 & -0.06 & 0.3 & 0.88 & -0.78 & -0.72 & 0.77 & -0.57 & -0.54 & 0.35 & -0.68 & -0.86 & 0.48 & 0.6 & 0.76 & -0.86 \\
-0.67 & -0.53 & -0.23 & -0.47 & 0.21 & 0.65 & 0.29 & -0.65 & -0.66 & -0.76 & 0.16 & 0.79 & -0.21 & 0.83 & 0.46 & 0.65 & -0.38 & -0.37 & 0.5 & -0.86 \\
0.5 & -0.82 & 0.07 & 0.12 & 0.83 & 0.12 & -0.03 & -0.78 & 0.24 & -0.16 & 0.36 & -0.76 & 0.95 & -0.05 & 0.71 & -0.38 & 0.77 & 0.92 & 0.57 & 0.67 \\
0.08 & 0.14 & 0.37 & 0.64 & -0.82 & 0.51 & 0.78 & -0.81 & -0.85 & 0.46 & -0.97 & -0.13 & 0.48 & 0.29 & 0. & 0.9 & -0.91 & -0.56 & -0.42 & 0.26 \\
-0.96 & 0.9 & -0.47 & 0.01 & -0.94 & -0.52 & -0.77 & -0.62 & 0.62 & -0.14 & 0.98 & 0.05 & -0.3 & -0.88 & -0.01 & -0.69 & -0.24 & -0.7 & -0.39 & -0.57 \\
0.82 & -0.18 & 0.58 & -0.83 & -0.34 & -0.89 & -0.81 & 0.07 & 0.54 & -0.27 & -0.23 & -0.76 & -0.84 & -0.49 & 0.11 & 0.41 & -0.37 & -0.24 & -0.31 & 0.99 \\
-0.66 & 0.69 & -0.08 & 0.16 & 0.98 & 0.75 & -0.94 & 0.27 & 0.41 & -0.99 & -0.27 & 0.36 & -0.59 & 0.8 & 0.43 & -0.63 & -0.4 & -0.57 & -0.14 & 0.07 \\
-0.12 & -0.51 & -0.17 & 0.61 & 0.87 & 0.74 & 0.35 & -0.48 & -0.42 & 0. & -0.86 & -0.47 & -0.53 & -0.99 & -0.37 & -0.16 & 0.58 & -0.95 & -0.82 & 0.8 \\
0.56 & -0.66 & -0.99 & -0.66 & 0.57 & -0.18 & 0.92 & 0.14 & -0.27 & 0.73 & -0.36 & -0.45 & 0.84 & -0.27 & -0.46 & -0.75 & 0.62 & -0.89 & 0.39 & 0.14 \\
0.07 & 0.04 & 0.98 & -0.43 & -0.73 & 0.97 & 0.56 & 0.19 & 0.63 & -0.24 & 0.22 & 0.63 & -0.75 & 0.05 & 0.34 & 0.6 & -0.04 & -0.15 & 0.72 & 0.42 \\
-0.45 & -0.9 & 0.84 & -0.09 & 0.8 & 0.78 & 0.72 & 0.94 & 0.15 & -0.46 & 0.64 & -0.34 & -0.79 & 1. & -0.47 & 0.53 & -0.38 & -0.81 & 0.69 & 0.89 \\
-0.54 & -0.83 & -0.57 & 0.71 & 0.23 & -0.15 & -0.85 & -0.93 & -0.7 & 0.43 & -0.98 & 0.76 & -0.95 & 0.06 & -0.35 & 0.99 & 0.91 & -0.19 & -0.29 & 0.76 \\
-0.78 & -0.86 & 0.05 & -0.69 & 0. & -0.98 & 0.35 & 0.12 & -0.67 & 0.38 & -0.69 & 0.36 & -0.82 & -0.34 & -0.79 & 0.73 & 0.07 & 0.99 & -0.07 & -0.69
\end{array}\right)$$

E_n $\qquad$ $R_{mn} = \langle E_m | O | E_n \rangle$

Microscopics





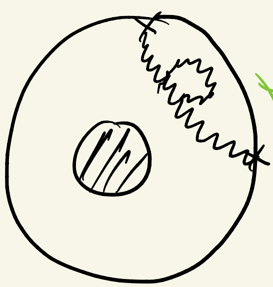
$S = \frac{A}{4G_N}$

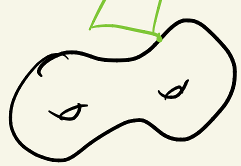
Semi-classical gravity

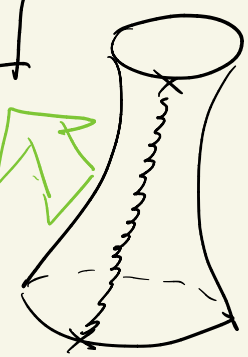
=

The thy of the stat. distribution of

$\{E_n, R_{mn}\}$







Today $\rightarrow$ Focus on operator statistics

The ETH Ansatz :

$$\boxed{\langle E_m | O | E_n \rangle = \delta_{mn} f_o(\bar{E}) + R_{mn} e^{-S(\bar{E})/2} g_o(\bar{E}, \delta E)}$$

- $f_o, g_o \rightarrow$ smooth fcts, microcan. 1 and 2 pt fcts
- $R_{mn} \rightarrow$ Indep. random numbers, 0 mean, 1 variance

Today $\rightarrow$ Focus on operator statistics

The ETH Ansatz :

$$\boxed{\langle E_m | O | E_n \rangle = \delta_{mn} f_O(\bar{E}) + R_{mn} e^{-S(\bar{E})/2} g_O(\bar{E}, \delta E)}$$

- f_O, g_O $\rightarrow$ smooth fcts , microcan. 1 and 2 pt fcts
- R_{mn} $\rightarrow$ Indep. "pseudorandom" numbers, 0 mean , 1 variance

R_{mn} not actually random, fixed in any theory

R_{mn} are neither indep. nor Gaussian

$\Rightarrow$ Inconsistent with higher point functions

Need non-trivial $\overline{R_{ij} R_{jk} R_{k\ell} R_{\ell i}}$ (= quartic moment with cyclic struct.]

R_{mn} are neither indep. nor Gaussian

$\Rightarrow$ Inconsistent with higher point functions

Need non-trivial $\overline{R_{ij} R_{jk} R_{kl} R_{li}}$ (= quartic moment with cyclic struct.)

However: $$\boxed{R_{mn}\big|_{k\text{-th moment}} \sim e^{-\frac{k-1}{k} S}}$$

[Foini, Kurchan]

The important point: Higher moments are supressed

ETH: QM $\longrightarrow$ CFT

$$\langle E_m | O | E_n \rangle = \langle O_m \; O \; O_n \rangle = C_{nmO}$$

$\Delta_{n,m} \longrightarrow \infty$

Δ_O fixed

ETH only applies to primaries

But in a CFT, doesn't capture all the dynamics

$$\left.\begin{array}{ll} C_{ijk} & \Delta_{i,j,k} \longrightarrow \infty \\ C_{OOi} & \Delta_i \longrightarrow \infty \end{array}\right\} \; ??$$

New observables / probes of chaos

$$Z_{g=2}(\beta) = \sum_{O_1, O_2, O_3} |C_{123}|^2 e^{-\beta(\Delta_1 + \Delta_2 + \Delta_3)}$$

The genus-2 SFF:

$$\boxed{F(t) = Z_{g=2}(\beta + it)\, Z_{g=2}(\beta - it)}$$

ETH / RMT $\Rightarrow$ doesn't offer much insight here...

ORH conjecture

[AB, de Boer]

In a chaotic CFT:

$$C_{00i} = f_1(\bar{E})\, R_i$$

$$C_{ijk} = f_1(\bar{E}, \delta E_i)\, R_{ijk}$$

pseudorandom variables
0 mean, 1 variance

Gravitational implications

Semi-classical gravity has access to the smooth fcts.

But no more $\Rightarrow$ explains lack of factorization

Plan

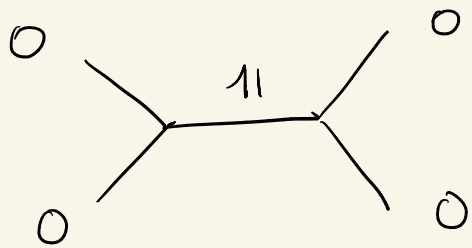
1. Some evidence for ORH

2. Wormhole implications

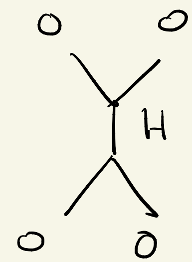
How to check ORH ?

Numerically $\longrightarrow$ Way beyond current bootstrap

Consistency checks $\longrightarrow$ constraints from cross + mod. inv.



$= \sum_{H}$



$\Rightarrow \sum_{H} |C_{OOH}|^2$

[Pappadulo, Rychkov, Espin, Rattazzi]

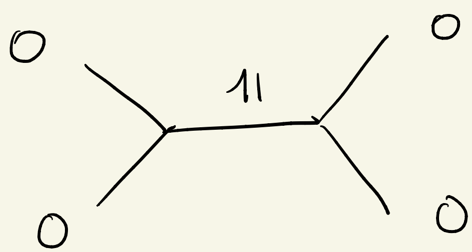
$\Rightarrow$ $\boxed{\text{Asymptotic formulas}}$

[many people]

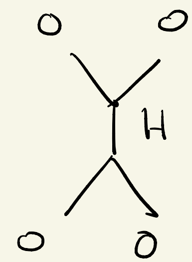
How to check ORH ?

Numerically $\longrightarrow$ Way beyond current bootstrap

Consistency checks $\longrightarrow$ constraints from cross + mod. inv.



$= \sum_H$



$\Rightarrow \sum_H |C_{OOH}|^2$

[Pappadopulo, Rychkov, Espin, Rattazzi]

$\Rightarrow$ **Asymptotic formulas**

[many people]

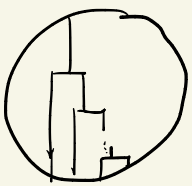
$$\sum_{i,j,k} |C_{ijk}|^2 \approx \left(\frac{27}{16}\right)^{3\Delta} e^{-3\pi\sqrt{\frac{c}{3}\Delta}}$$

[Cardy, Maloney, Maxfield]

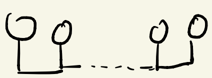
[Collier, Maloney, Maxfield, Tsiares]

Higher Moments

Trick: exploit modular invariance at genus-g



$$C_{ijk}\Big|_{\substack{k\text{-th moment}\\ \text{skyline}}} \sim e^{-\frac{5k-4}{4k}S}$$



$$C_{ijk}\Big|_{\substack{k\text{-th moment}\\ \text{comb}}} \sim e^{-\frac{9k-6}{8k}S}$$

[AB, de Boer, Liska-to appear]

Can also extract higher moments of

C_{LLH} , C_{HHH} in $d>2$

[Anous, AB, de Boer, Liska-to appear]

A generating function

$$Z[J_{abc}] = \exp\Big[f_1 \, J_{abc} J^{abc} + f_2 \, J_{aab} J^{bcc} + \sum_i g_i \, CCCC|_{i\text{-type contraction}} + \dots \Big]$$

$$\boxed{\overline{C \cdots C} = \frac{\delta}{\delta J} \cdots \frac{\delta}{\delta J} Z \Big|_{J=0}}$$

The functions $f_i, g_i, \dots$ can be extracted

from asymptotic formulas

ORH from RMT ?

We can derive a form of ETH from RMT

$$\mathcal{O} = \sum_\alpha \lambda_\alpha |\alpha\rangle\langle\alpha| \qquad \langle\alpha|E_n\rangle = U_{\alpha n}$$

Haar-Random

[Altland, Bagrets, Nayak, Sonner, Vielma]

$\mathbb{O}$: linear operator on $\mathcal{H}^{\otimes 3}$

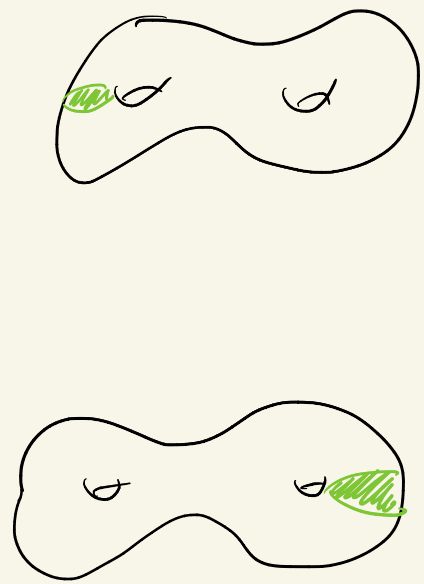
$$\langle ijk| \mathbb{O} |lmn\rangle = C_{ijk} C_{lmn}$$

Assume $\mathbb{O}$ is Haar-Random $\Rightarrow$ derive ORH

[AB, de Boer, Nayak, Sonner - to appear]

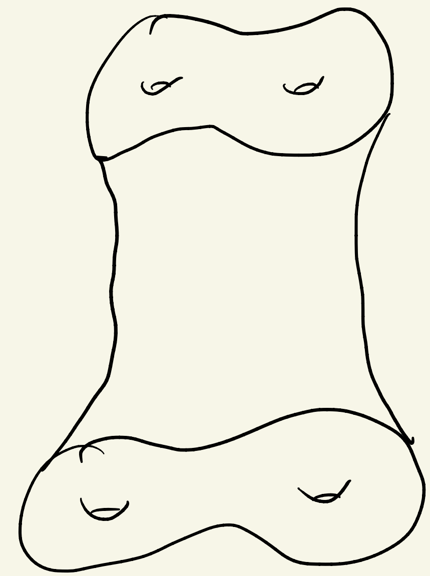
Implications for gravity

$$Z_{g=2} \times Z_{g=2}\Big|_{grav} =$$



Disconnected Handlebodies

$+$



Connected genus-2 wormhole

$$\approx e^{\frac{c}{2}\frac{\pi^2}{\beta}} + 1$$

Vanishing on-shell action

$$Z_{g=2} \times Z_{g=2}\Big|_{\mathrm{ORH}} \approx \sum_{\Delta_i} C\,C^*\,C\,C^*\,e^{-6\beta\Delta}$$

$$e^{\frac{c}{2}\frac{\pi^2}{\beta}} + \sum_{\Delta} e^{-6\beta\Delta}$$

↳ No large saddle

≈ 1

Add quartic moments:

$$\sum_{\Delta} CCCC\big|_{\text{skyline}}\, e^{-6\beta\Delta} = \sum_{\Delta} e^{-6\beta\Delta}$$

$\Rightarrow$ Same order! To check if 1-loop determinants match

need genus-2 + genus-3 handlebodies

A new connected saddle?

$$Z_{\text{dumbbell}} = \sum C_{iij} C_{jkk'} e^{-3\beta\Delta}$$

$$\left(Z_{\text{dumbbell}}\right)^2 \Big|_{\text{Comb}} \sim e^{\frac{25c - 360\Delta_\chi}{288} \frac{\pi^2}{\beta}}$$

If Δ_χ small enough $\rightarrow$ New large connected saddle, bigger than genus-2 wormhole!

A new connected saddle?

$$Z_{\text{dumbbell}} = \sum C_{iij} C_{jkk}' e^{-3\beta\Delta}$$

$$\left(Z_{\text{dumbbell}}\right)^2 \Big|_{\text{Comb}} \sim e^{\frac{25c - 360\Delta_\chi}{288} \frac{\pi^2}{\beta}}$$

If Δ_χ small enough $\Rightarrow$ New large connected saddle, bigger than genus-2 wormhole!

$$\Delta_\chi < \frac{c-1}{12}\left(1 - \frac{1}{6^2}\right)$$ $\Rightarrow$ weight of $\mathbb{Z}_6$ conical defect.

Open Questions

- ORH predicts new wormhole solution, why haven't we found it? Matter supported?

- There seems to be 2 possibilities:

Typicality / Haar Averages + Asymptotic formulas $\Rightarrow$ predicts wormholes

or

Wormholes = everything you cannot predict from Typicality

Multi-trace terms in $Z[J]$?

Thank You!