The Ising model, gravity and evading the black hole information paradox

Romuald A. Janik

Jagiellonian University
Kraków, Poland

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Outline

Motivation

Holography for Virasoro minimal models?

A particular Ising model observable

Gravity interpretation of the Ising model results

Evading the black hole information paradox

Summary

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Use AdS/CFT to learn about gravity:

QFT on the boundary $\Longrightarrow$ bulk theory with gravity

- **Gravity $\equiv$ subsector of bulk theory dual to the energy-momentum tensor**
- Generically this is **not** pure gravity but rather **gravity with matter**
- AdS/CFT provides, in principle, **a fully quantum definition** of this specific **gravity+matter** theory...

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Why is this difficult?

Dichotomy:

1. Need good control of boundary CFT
2. Need semiclassical gravity regime for good interpretation

E.g. we can easily do perturbative computations at low N_c in $\mathcal{N} = 4$ SYM, but we do not know what they mean on the bulk side!

But of course, the deeply intermingled regime of quantum gravity and matter (far from semiclassicality) is of great interest...

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We can get insight into (quantum) gravity with matter even from Ising model CFT

(and other minimal models)

Ad 1) exactly solvable! ✓

Ad 2) very far from $c \to \infty$...

consider the theory at large temperature T $\sim$ ✓

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Holography for Virasoro minimal models?

3D gravity $\equiv$ a pair of $SL(2,\mathbb{R})$ Chern-Simons theories

Heuristics:

1. Impose asymptotically AdS boundary conditions

$$\text{3D } SL(2,\mathbb{R}) \text{ CS} \big/_{asympt\ AdS} \equiv \text{2D } SL(2,\mathbb{R})\ WZW \big/_{J^+ = 1}$$

2. **Bershadsky-Ooguri construction '89:** Impose $J^+(z) = 1$ using BRST cohomology

$$SL(2,\mathbb{R})\ WZW \big/_{J^+ = 1} \quad \equiv \quad \text{Virasoro minimal model CFT}$$

on the level of Virasoro representations

Completely quantum statement! No large parameter required!

Matter fields $\equiv$ CS Wilson lines

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Heuristic "holographic" quantization of Chern-Simons

- We can consider the CS $SL(2,\mathbb{R})$ gauge fields as **quantum operators** $\widehat{A}(z,\bar{z},\rho)$, $\widehat{\bar{A}}(z,\bar{z},\rho)$ in the boundary CFT

$$\widehat{A}(z,\bar{z},\rho) = b^{-1}\left(t^{+} - \frac{6}{c}T(z)t^{-}\right) b dz + b^{-1}\partial_\rho b d\rho$$
$$\widehat{\bar{A}}(z,\bar{z},\rho) = -b\left(t^{-} - \frac{6}{c}\overline{T}(\bar{z})t^{+}\right) b^{-1} d\bar{z} + b\partial_\rho b^{-1} d\rho$$

- We can evaluate the thermal average:

$$\left\langle \widehat{A}(z,\bar{z},\rho)\right\rangle_T = A_{BTZ}(\rho) \qquad \left\langle \widehat{\bar{A}}(z,\bar{z},\rho)\right\rangle_T = \bar{A}_{BTZ}(\rho)$$

- We thus expect to be dealing with a BTZ black hole even for the Ising CFT

$$g_{\mu\nu} = \frac{1}{2}\operatorname{tr}(A_\mu - \bar{A}_\mu)(A_\nu - \bar{A}_\nu)$$

- Approximate semiclassicality at high temperatures:

$$\langle T(z_1)T(z_2)\rangle_T = \langle T(z_1)\rangle_T \cdot \langle T(z_2)\rangle_T + \mathcal{O}\left(e^{-\#\, T|z_{12}|}\right)$$

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How to probe a black hole?

1. On the gravity side:

Throw matter into the black hole...

2. On the CFT side:

Perturb the thermal density matrix

$$\rho_T \longrightarrow \rho_T + \delta\rho \qquad \delta\rho \propto i\,[\rho_T, \int \varepsilon\, dx]$$

and study its temporal evolution...

by measuring e.g. $\langle \varepsilon(t) \rangle$

Focus on linearized QNM-like dynamics...

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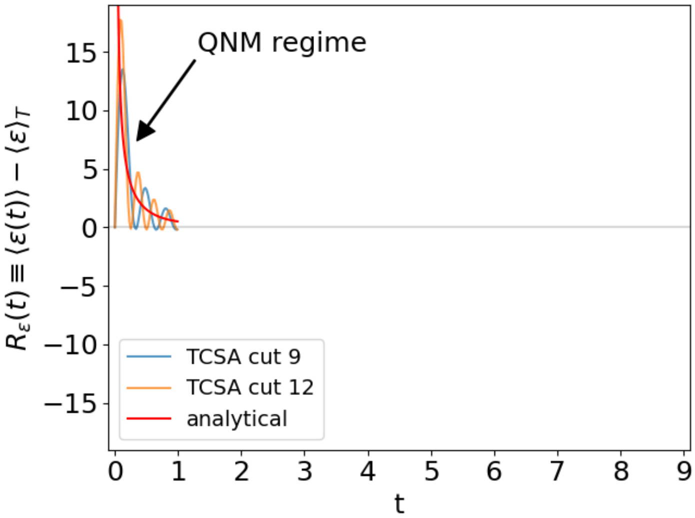
Specialize to the Ising model...

Ising model CFT at $T > 0$

Key question: How to understand the reemergence of the intact signal from the bulk black hole perspective?

Ising model CFT at $T > 0$



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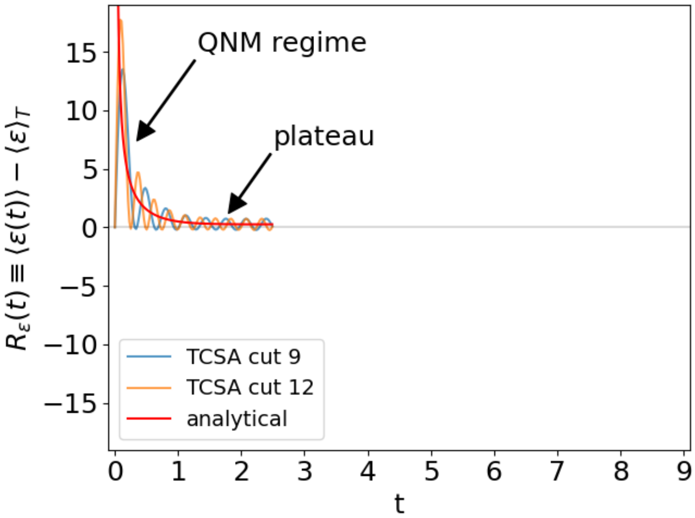

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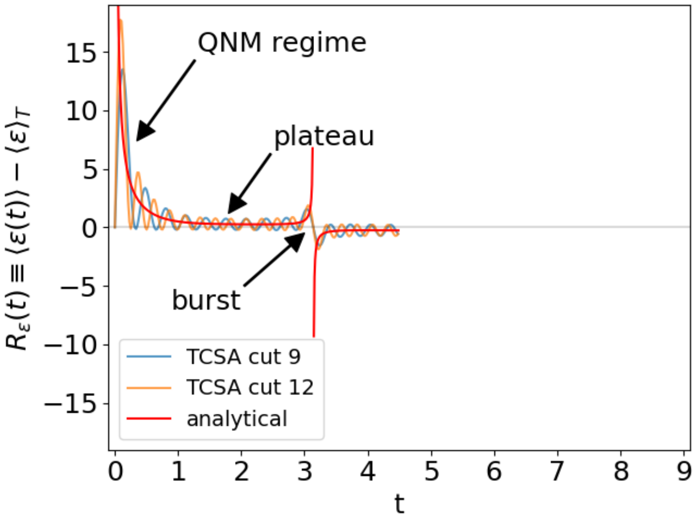

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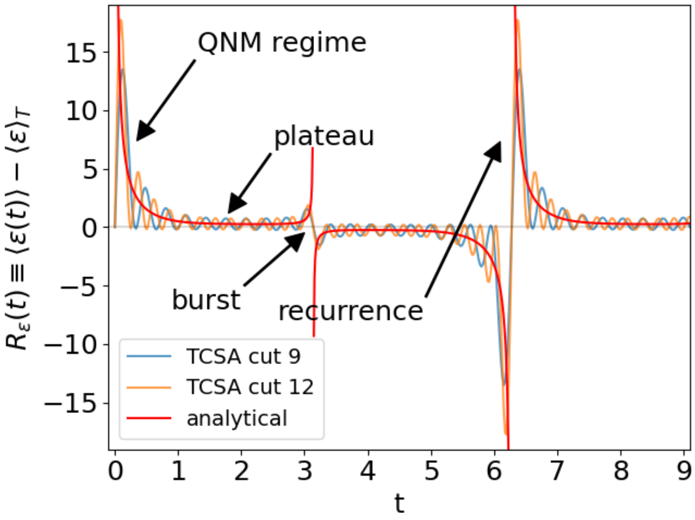

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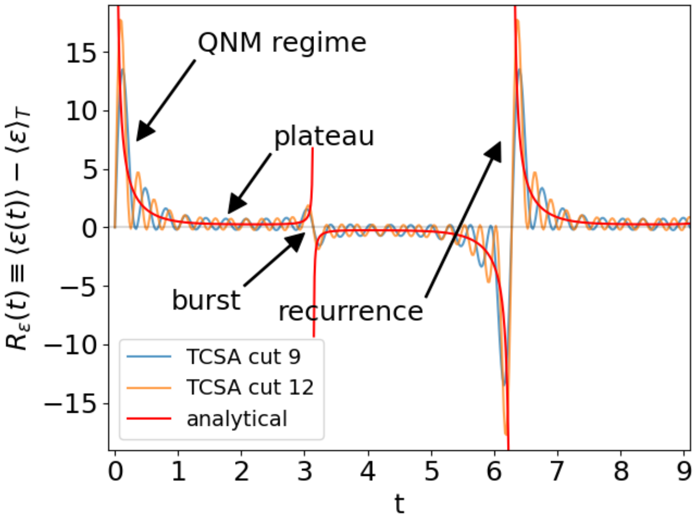

Key question: **How to understand the reemergence of the intact signal from the bulk black hole perspective?**

CFT origin of the recurrence/periodicity

In the Ising model CFT, the observable can be computed exactly, starting from the 2-point function on the torus, and carefully evaluating the integrated retarded 2-point function:

$$R_\varepsilon(t) = const \cdot \frac{\theta_2(t) + \theta_3(t) + \theta_4(t)}{\theta_1(t)}$$

- $R_\varepsilon(t)$ is periodic irrespective of the value of the temperature!

$$R_\varepsilon(t + 2\pi) = R_\varepsilon(t)$$

- This means that the signal would reemerge **unchanged** after time 2π ($\equiv$ spatial circle size)
- Natural from the CFT point of view: level spacing $= 1$, $\Delta = 1$ for ε

  time $\sim$ inverse level spacing *(also in gravity)*
- More generally, for minimal models time evolution is always periodic

$$e^{i\, H_{CFT}\, T_{period}} \equiv id$$

with T_{period} being an integer multiple of 2π

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CFT origin of the recurrence/periodicity

In the Ising model CFT, the observable can be computed exactly, starting from the 2-point function on the torus, and carefully evaluating the integrated retarded 2-point function:

$$R_\varepsilon(t) = const \cdot \frac{\theta_2(t) + \theta_3(t) + \theta_4(t)}{\theta_1(t)}$$

- $R_\varepsilon(t)$ is periodic irrespective of the value of the temperature!

$$R_\varepsilon(t + 2\pi) = R_\varepsilon(t)$$

- This means that the signal would reemerge **unchanged** after time 2π ($\equiv$ spatial circle size)
- Natural from the CFT point of view: level spacing = 1, $\Delta = 1$ for ε

  time $\sim$ inverse level spacing *(also in gravity)*
- More generally, for minimal models time evolution is always periodic

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Black hole information paradox

- **Classical case:**

  pure state $\longrightarrow$ collapse $\longrightarrow$ evaporation $\longrightarrow$ mixed state???

- Apparent mismatch between unitary evolution and causal structure

- **Here:** *c.f. Maldacena hep-th/0106112 (eternal BH paper)*

  perturbed thermal $\longrightarrow$ falls into BH $\longrightarrow$ reemerges intact!!!

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- **Gravity** $\equiv A$ and $\bar{A}$ Chern-Simons gauge fields involving the energy-momentum tensor operator of the CFT
- **Matter fields** $\equiv$ **Wilson line networks**

we use approach of Fitzpatrick, Kaplan, Li, Wang

$$P \exp \int_C A_\mu^a J^a dx^\mu \quad + \quad \text{trivalent junctions (OPE of the CFT)}$$

QNM regime

$$\left(\frac{a}{\sinh a z_{fi}} \right)^{2h} \cdot h.c. \longrightarrow e^{-2\pi T t}$$

where $a = \pi T$ $\quad (z = x + t,\ \bar{z} = x - t)$

Agrees with the QNM mode of the appropriate BTZ black hole...

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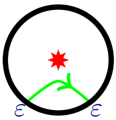

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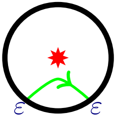

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The plateau

$$\propto e^{-\frac{\pi^2}{2}T}$$

The σ loop is reminiscent of a scalar loop around the horizon

Kraus, Maloney *(in the context of torus 1-pt functions)*

$$\propto e^{-2\pi r_+ \Delta} \quad \xrightarrow{\Delta=\frac{1}{8}} \quad e^{-\frac{\pi^2}{2}T}$$

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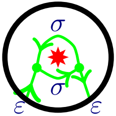

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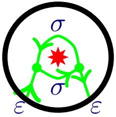

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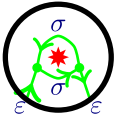

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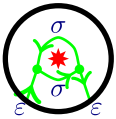

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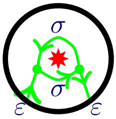

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The recurrence/periodicity

- Incorporate Wilson lines winding around the singularity

$\cdots \longrightarrow \quad \sum_{n=-\infty}^{\infty} \frac{a}{\sinh a(z_{fi}+2\pi n)}$

- Incorporate antiholomorphic part:

$$\sum_{n=-\infty}^{\infty} \frac{a}{\sinh a(z_{fi}+2\pi n)} \cdot \frac{a}{\sinh a(\bar{z}_{fi}+2\pi n)}$$

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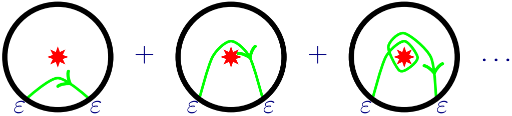

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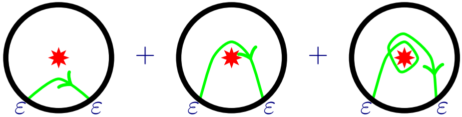

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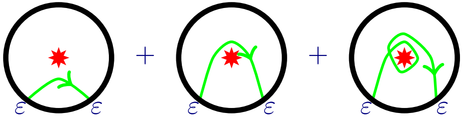

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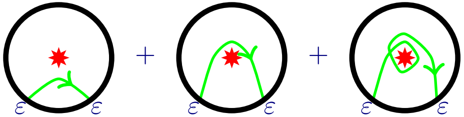

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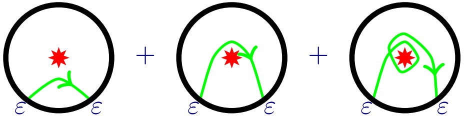

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which leads to the periodicity of $R_\varepsilon(t)$

- From the exact CFT answer, we can read off the allowed windings of the holomorphic and antiholomorphic Wilson lines...
- In terms of Wilson line networks the two results come from

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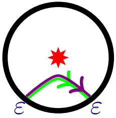

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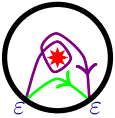

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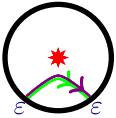

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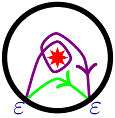

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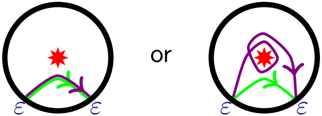

Consequences:

1. Wilson line trajectories for holomorphic and antiholomorphic are largely independent! Wilson lines $\sim 1^{st}$ quantized matter...
2. Matter field $\longrightarrow$ pair of fields, one interacting only with A, the other with $\bar{A}$ *not a scalar field!*
3. This implies that the fields can, in a specific way, ignore the geometry/causal structure
   (as the metric $g_{\mu\nu}$ and horizons, is only defined through **both** A and $\bar{A}$)

$$g_{\mu\nu} = \frac{1}{2}\,\mathrm{tr}\,(A_\mu - \bar{A}_\mu)(A_\nu - \bar{A}_\nu)$$

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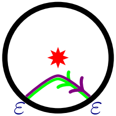

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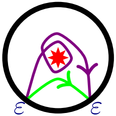

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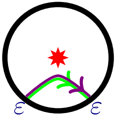

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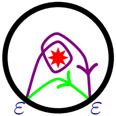

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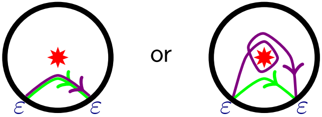

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   (as the metric $g_{\mu\nu}$ and horizons, is only defined through **both** A and $\bar{A}$)

$$g_{\mu\nu} = \frac{1}{2}\,\mathrm{tr}\,(A_\mu - \bar{A}_\mu)(A_\nu - \bar{A}_\nu)$$

4. In this way they **evade the black hole information paradox**
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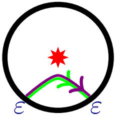
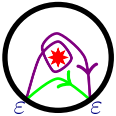


or



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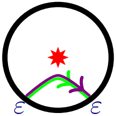

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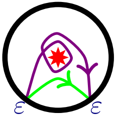

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Further comments

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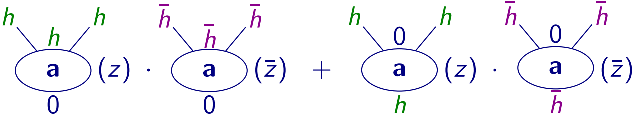

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