The Information Paradox and Two Dimensional CFT

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based on work with
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What Paradoxes?

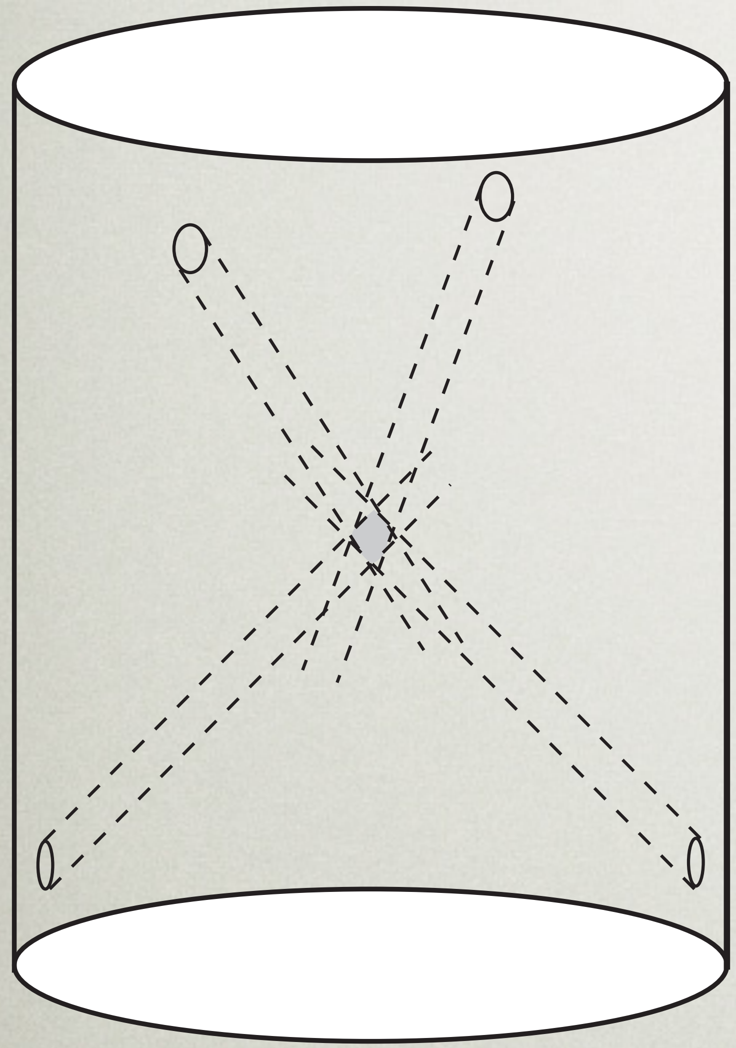
Qualitative disagreement between AdS gravitational field theory/perturbative string theory and exact, unitary Conformal Field Theory.

Two classes:

Easier = unambiguous discrepancies with CFT

Hard = potentially ambiguous questions about AdS observables

Unambiguous Disagreement: Bulk Point Singularities



(figure from Heemskerk, Penedones, Polchinski, & Sully)

Bulk field theory produces boundary correlators with "bulk point singularities" associated with scattering.

These singularities expected to be absent from exact CFTs.

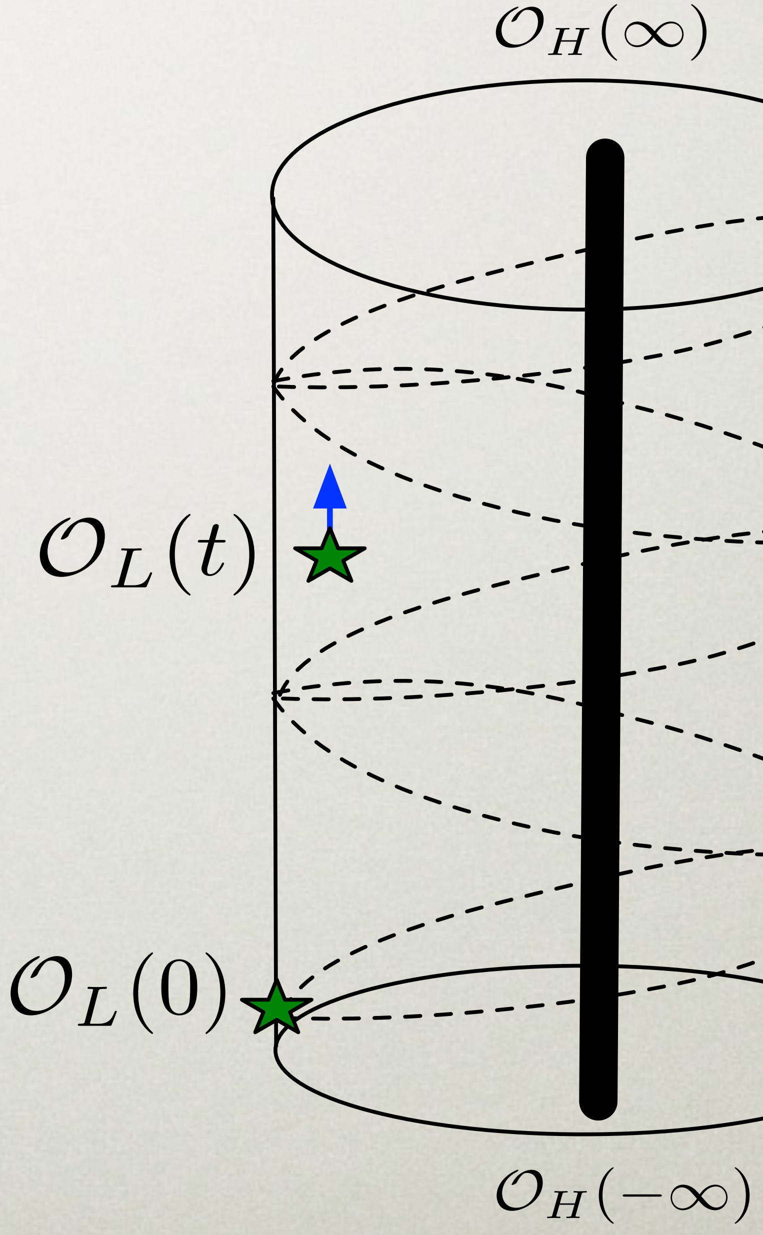
(Won't be our focus, but note that not all "easy" problems involve black holes.)

Unambiguous Disagreement: Late Time Correlations

Late time behavior of correlation functions in an AdS black hole background.

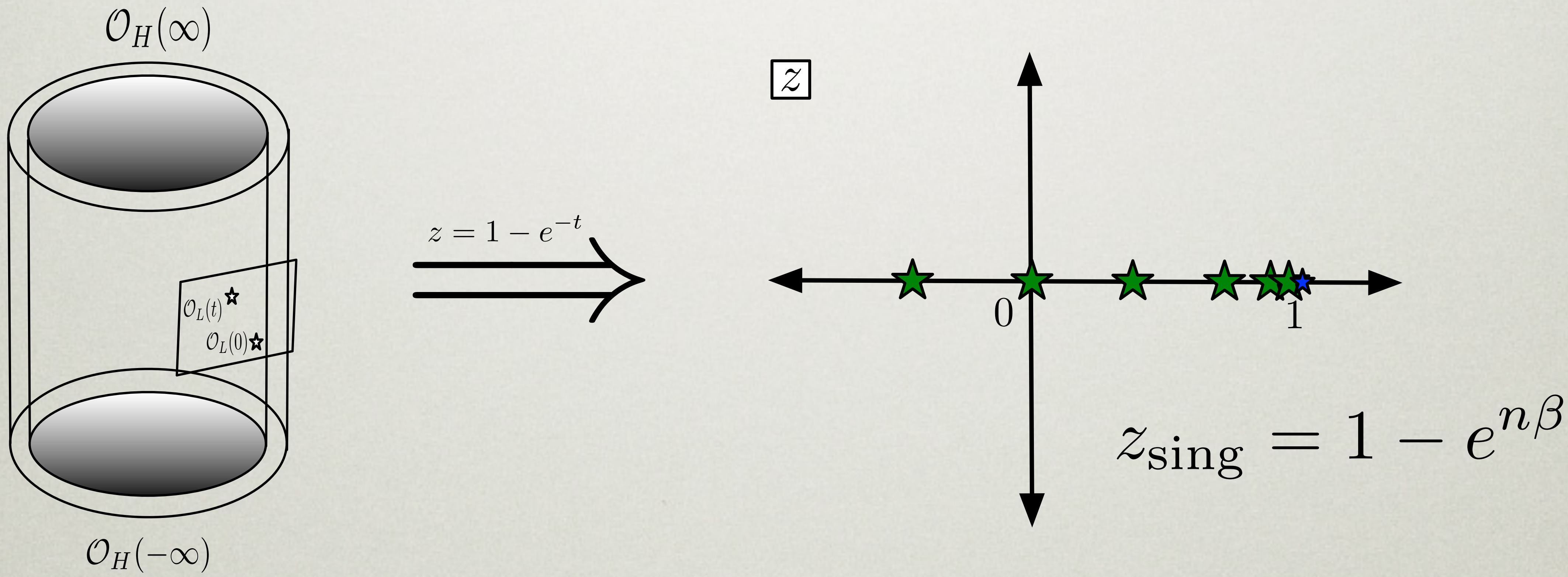
Does $\langle \mathcal{O}_L(t) \mathcal{O}_L(0) \rangle_{BH}$ decay forever?

Is the spectrum discrete?



Unambiguous Disagreement: Forbidden Singularities

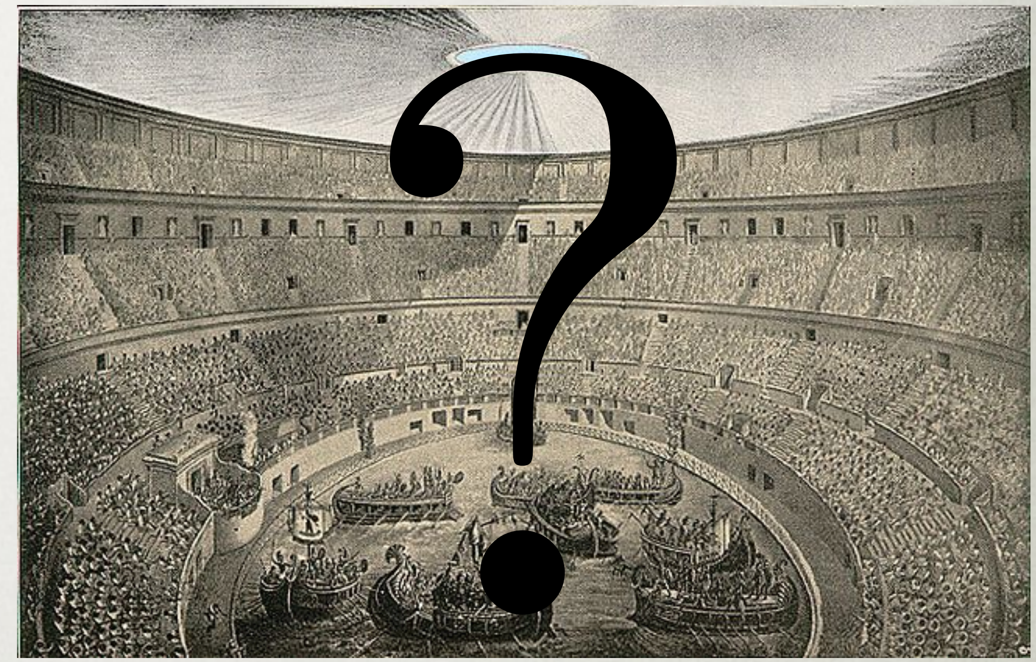
Forbidden Singularities due to Euclidean-time periodicity (KMS) in **pure state** black holes:



How well do high-energy **pure states mimic** the canonical ensemble?

"Hard" = Ambiguous (?) Problems

→



I. How ambiguous is bulk reconstruction? When/where/why/to what extent?

II. What do observers see near and across black hole horizons?

Our Approach

1) Identify the approximation within the CFT that agrees with the perturbative bulk description and produces (information loss) problems.

2) From the vantage point of this approximation, identify and compute the non-perturbative effects that resolve information loss problems.

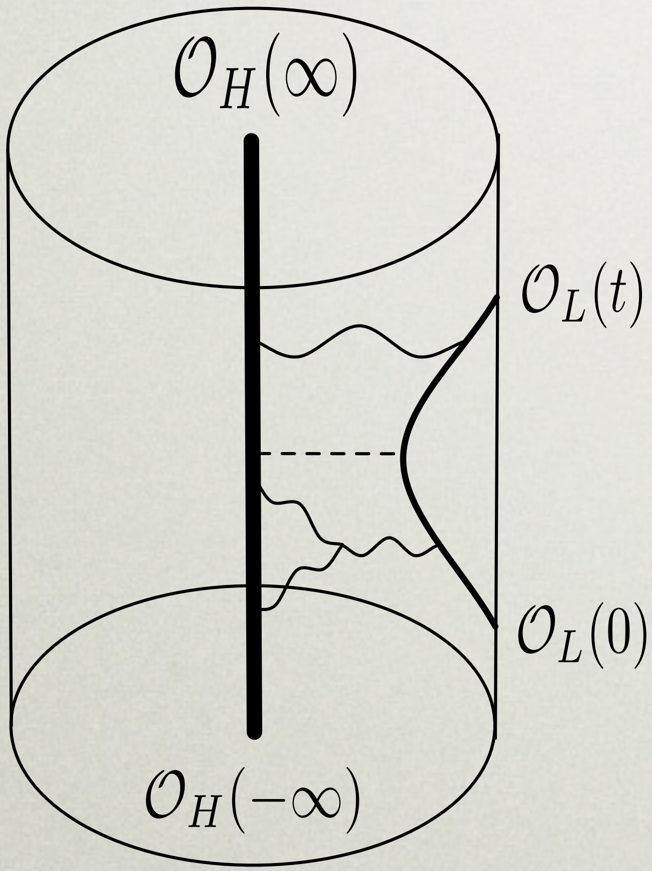
3) Comparing 1 & 2, what are the bulk implications?

In the approximation of (1), expect no ambiguities or firewalls. Both should come from effects in (2).

Old News about Heavy-Light Virasoro Blocks

What Observable (in AdS/CFT)?

$$\langle \mathcal{O}_H(\infty)\mathcal{O}_H(1)\mathcal{O}_L(z)\mathcal{O}_L(0)\rangle$$



Recall:

$$G_N = \frac{3}{2c}, \; m_{AdS} \sim h$$

We'll study light probes of heavy pure states.

Always expand in the $\mathcal{O}_L(z)\mathcal{O}_L(0)$ OPE channel.

Building Blocks for Correlators

Natural to **organize amplitudes** into **blocks**,
ie irreducible representations of the **symmetry**.

Flat space with Poincare symmetry, find partial waves.

In d>2 CFT, we have SO(d+1,1) conformal blocks
or conformal partial waves.

Building Blocks for 2d CFT Correlators

Virasoro conformal blocks encapsulate contributions from all states related by Virasoro:

$$\langle \mathcal{O}_1(\infty)\mathcal{O}_2(1)\mathcal{O}_3(z)\mathcal{O}_4(0)\rangle = \sum_{h,\bar{h}} P_{h,\bar{h}} \mathcal{V}_{h_i,h,c}(z)\mathcal{V}_{\bar{h}_i,\bar{h},c}(\bar{z})$$

This is interesting because: $g_{\mu\nu}(X) \leftrightarrow T_{\mu\nu}(x)$

and in 2d CFTs: $T(z) = \sum_n z^{-2-n} L_n$

Virasoro blocks know about quantum gravity.

Some Blocks Are More Interesting Than Others

(Ozmenoglu)

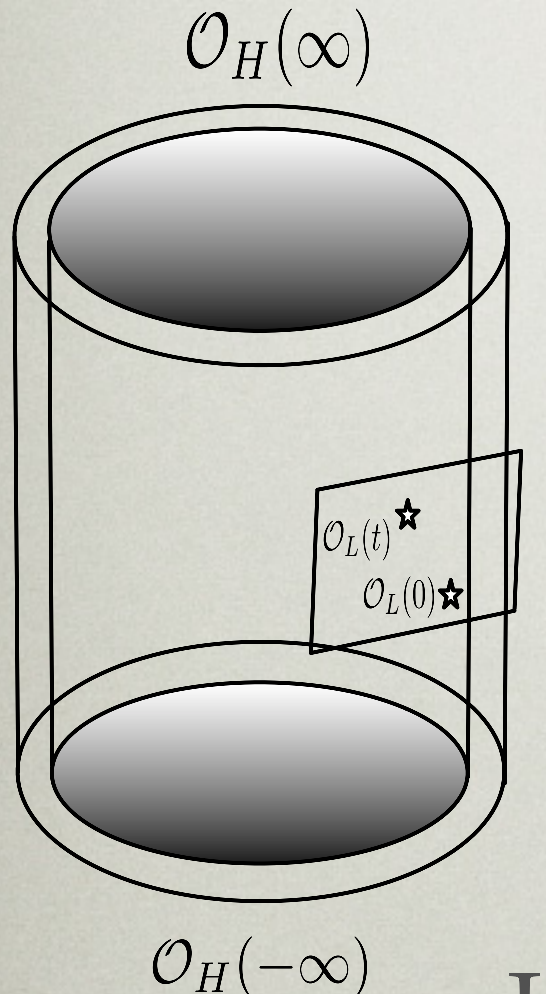
Most of the structure is present in each layer… but you have to know how to look.

Let's first study the heavy-light semiclassical approx:

$$c \to \infty \quad \text{with} \quad \frac{h_H}{c}, h_L \quad \text{fixed}$$

Example: Heavy-Light Vacuum Block as $c \to \infty$.

Semiclassical heavy-light Virasoro vacuum block:



$$\mathcal{V}(t) = \left(\frac{\pi T_H}{\sin(\pi T_H t)} \right)^{2h_L}$$

on the Euclidean cylinder, with

$$T_H = \frac{1}{2\pi}\sqrt{24\frac{h_H}{c} - 1}$$

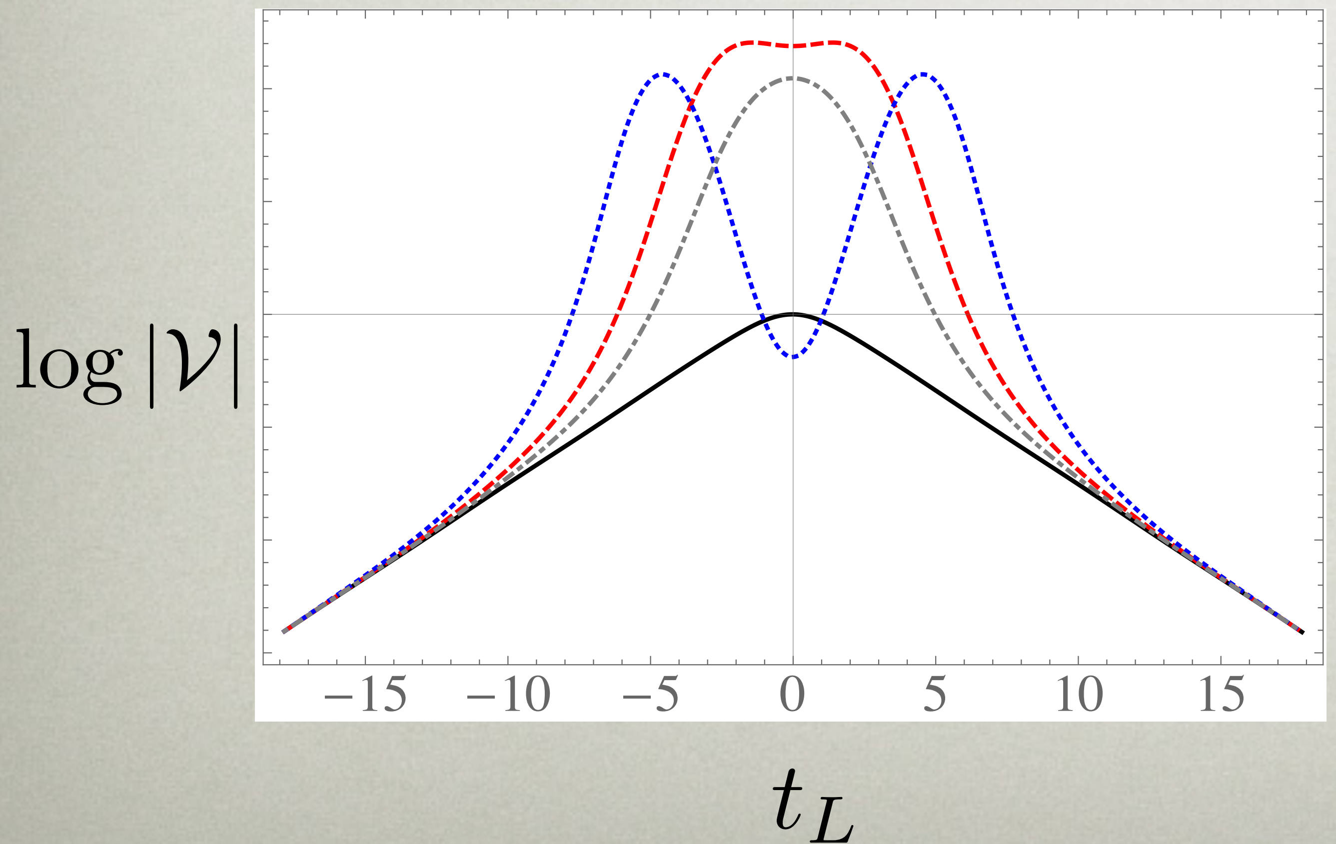
It knows the BTZ black hole temperature!

Let's note two features of this semiclassical result…

Late Time Information Loss from Virasoro Blocks

$$\mathcal{V}(t_L) = \left(\frac{\pi T_H}{\sinh(\pi T_H t_L)} \right)^{2h_L}$$

It decays exponentially at late **Lorentzian** times.



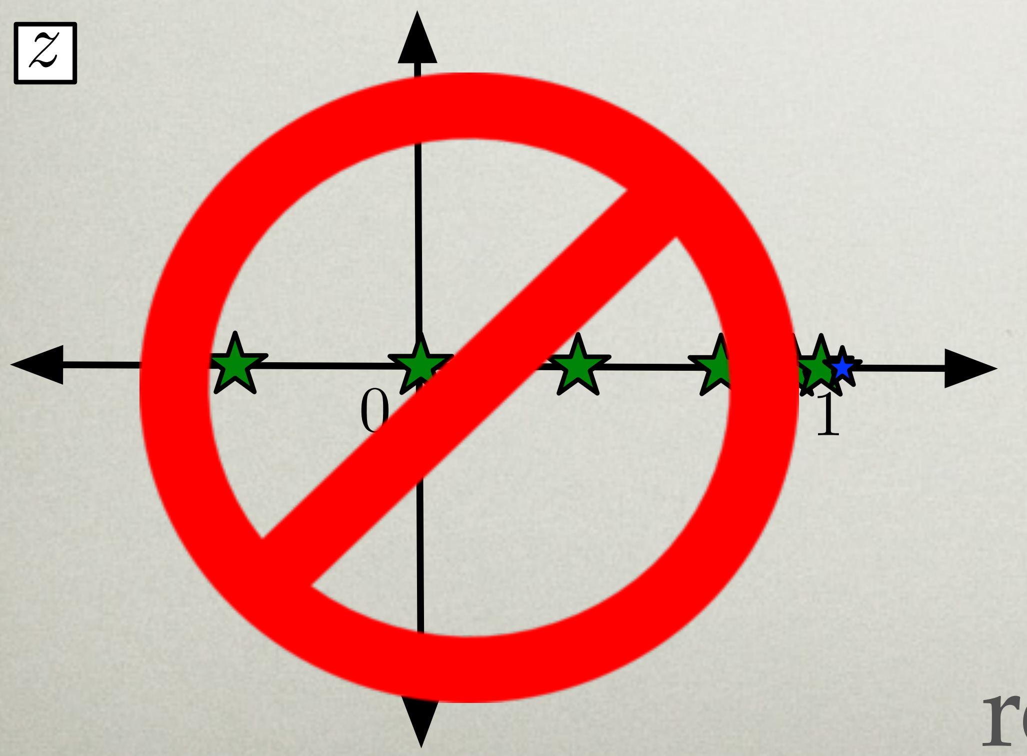
All semiclassical blocks decay at the same exponential rate:

$$\mathcal{V}(t_L) \propto e^{-2\pi h_L T_H t_L}$$

Forbidden Singularities from Virasoro Blocks

$$\mathcal{V}(t) = \left(\frac{\pi T_H}{\sin(\pi T_H t)} \right)^{2h_L}$$

It is **periodic in Euclidean time**, ie satisfies KMS.



This means that it has **forbidden singularities**:

$$z_{\text{sing}} = 1 - e^{n\beta}$$

representing Unitarity violation

Virasoro Blocks Encapsulate Quantum Gravity and Info Loss

- Black Hole Thermodynamics from Blocks
- Information loss comes from the blocks, and occurs block-by-block, largely independent of CFT data (ie spectrum and OPE coefficients)

So gravity is very robust/generic!

And we do not have to solve any particular theory.

Resolving Information Loss Problems and Implications for the Bulk

Exact Information about Virasoro Blocks and Gravity?

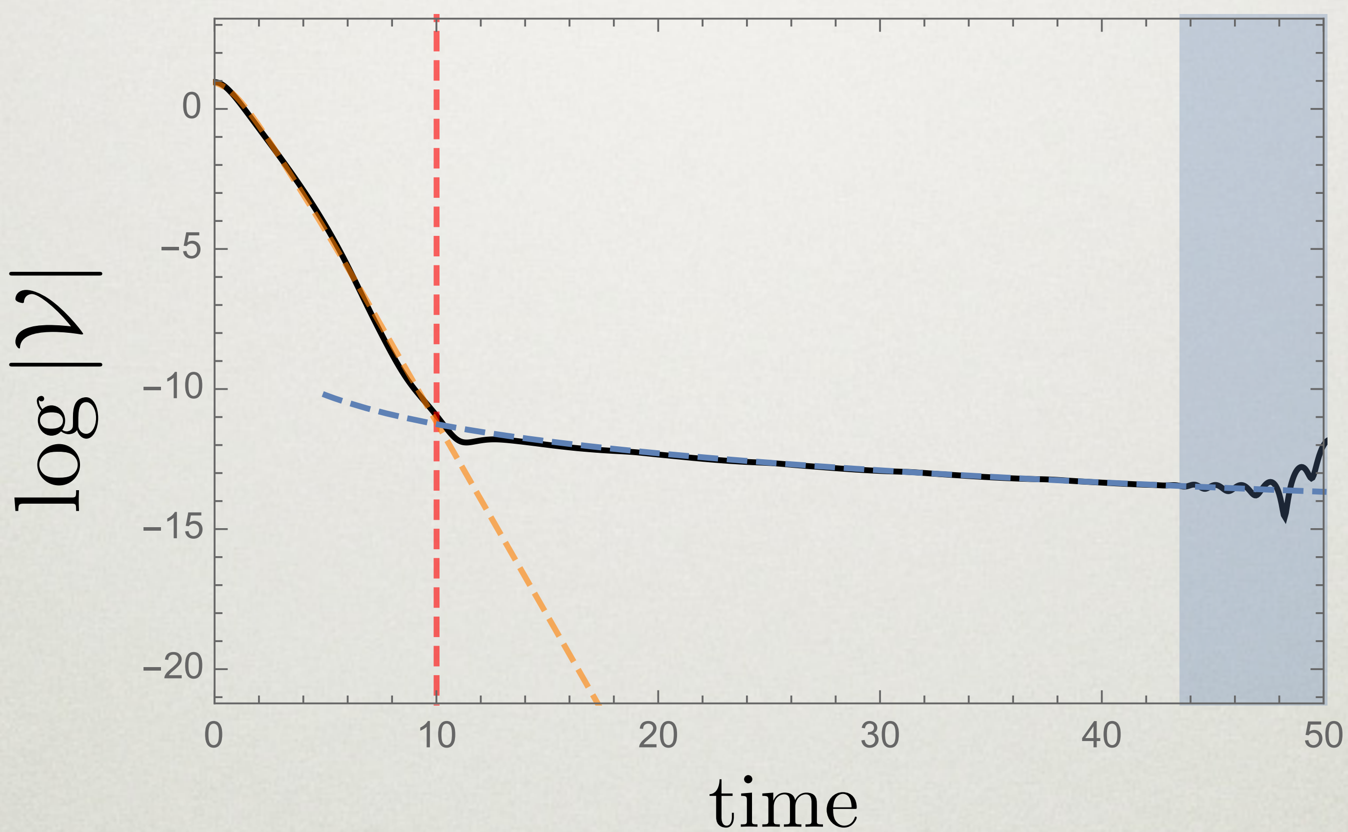
It is possible to get exact information using analytic continuation of degenerate states.

A simpler approach is to just evaluate the blocks numerically to very high precision using the Zamolodchikov recursion relations.

Let's look at the results…

Exact vs Semiclassical: Late Time Behavior

At late times the gravity prediction breaks down:



Early: $e^{-2\pi h_L T_H t_L}$ Late: $t_L^{-3/2}$

Transition at $t_D = \frac{\pi c}{6 h_L}$ predicted analytically.

Late Time Punchlines

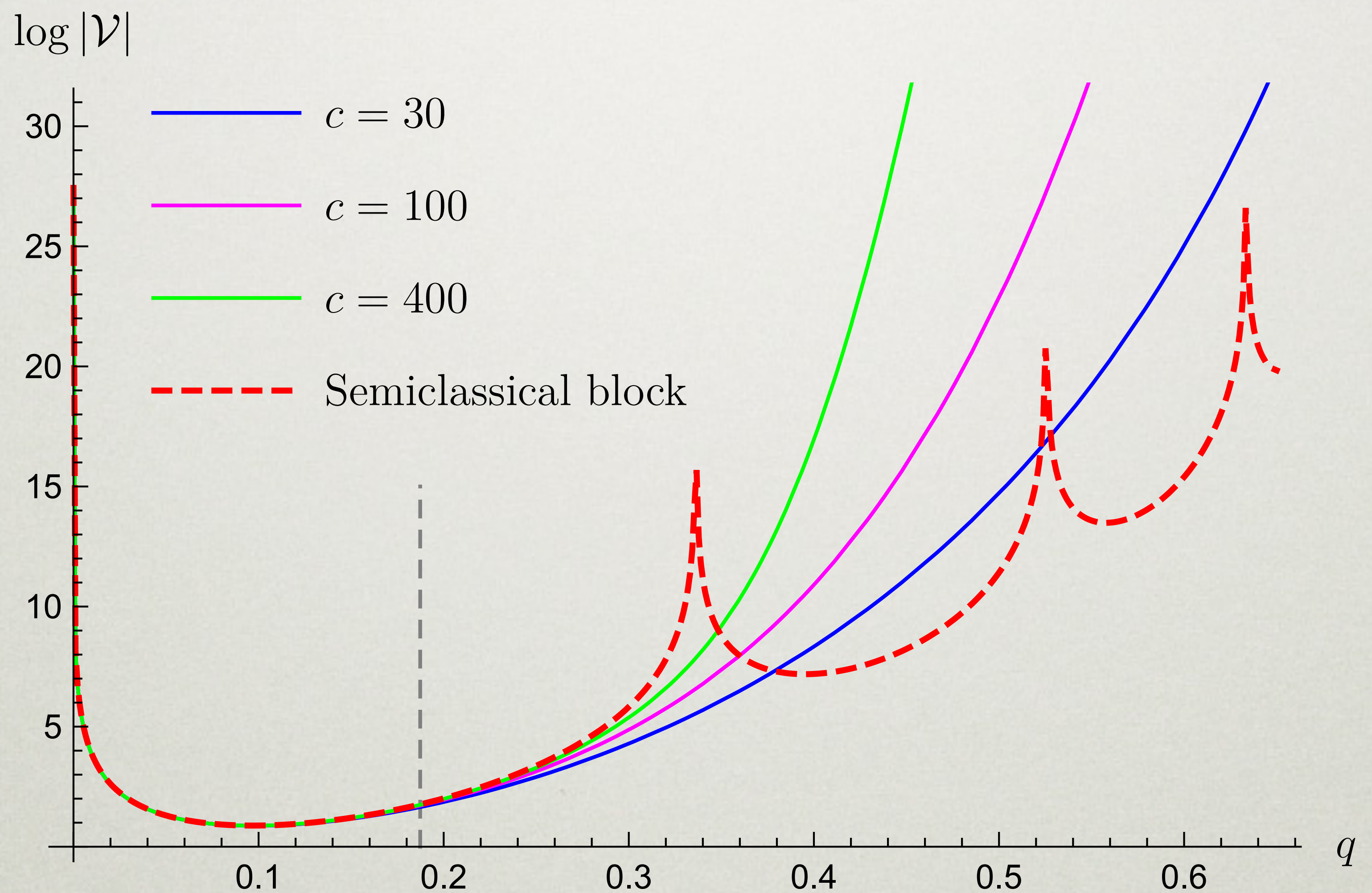
- Non-perturbative corrections are universal and qualitatively change late-time behavior of blocks
- Behavior of individual Virasoro blocks **ameliorates but does not resolve** late time decay

Late time behavior tests **discreteness of spectrum**…

Individual Virasoro blocks do not "know" that the spectrum must be discrete in all channels.

Euclidean-Time Periodicity and Forbidden Singularities

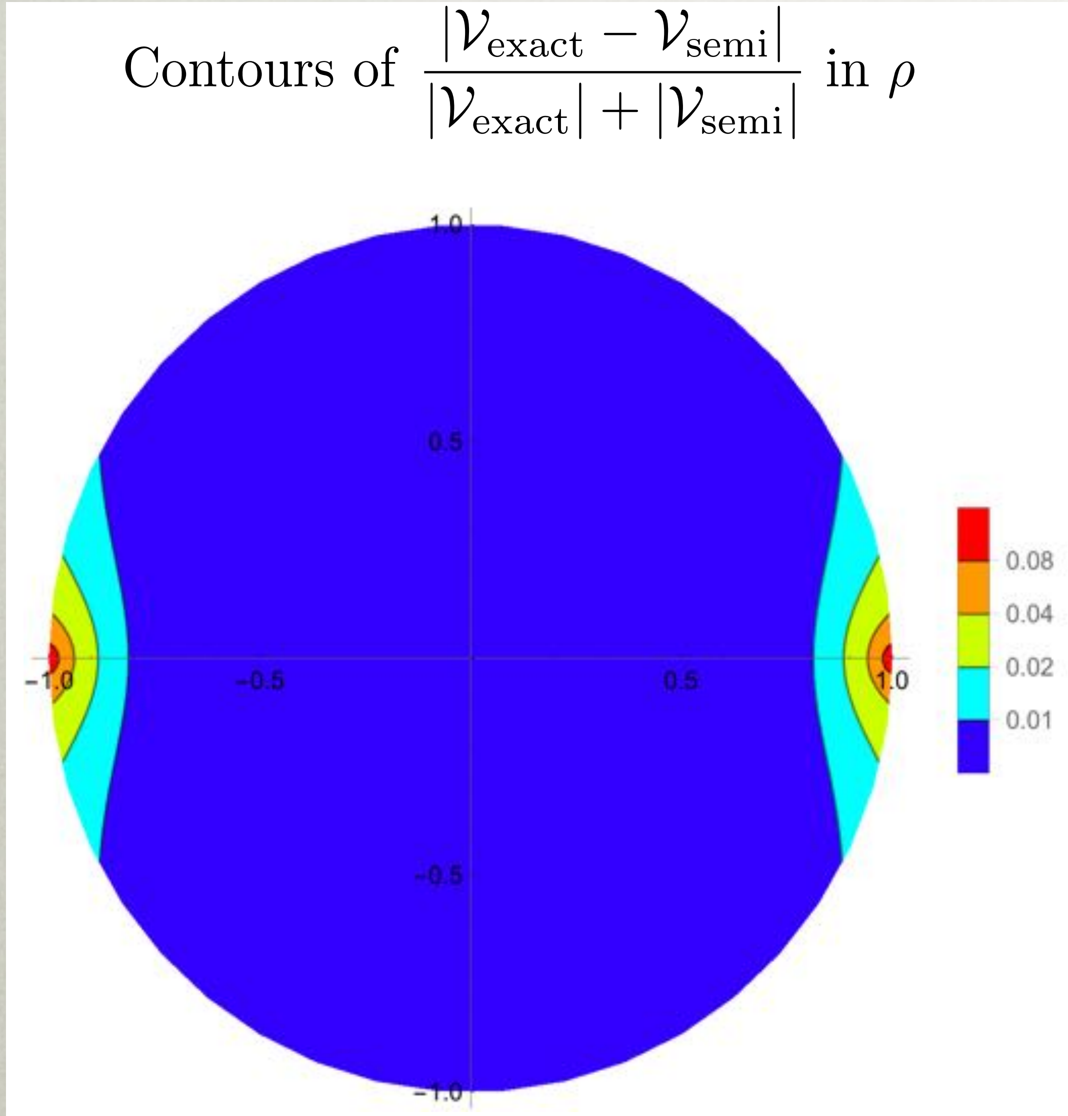
Semiclassical and exact blocks on the real axis:



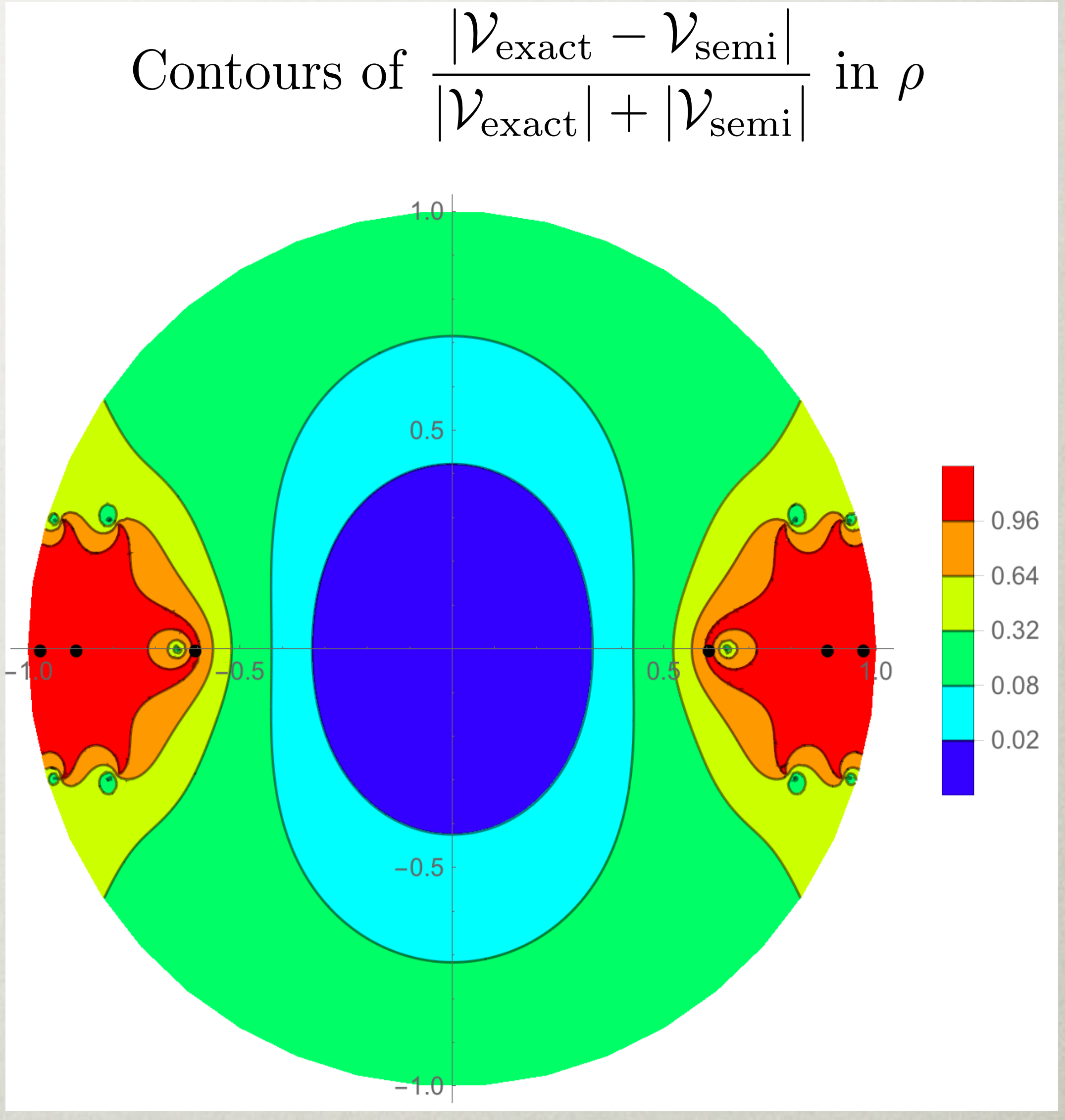
Semiclassical approximation **breaks down completely** beyond $t \approx \dfrac{1}{T_H}$ due to Stokes phenomena.

Semiclassical Approximation in the Euclidean Region

Without a Black Hole



With a Black Hole



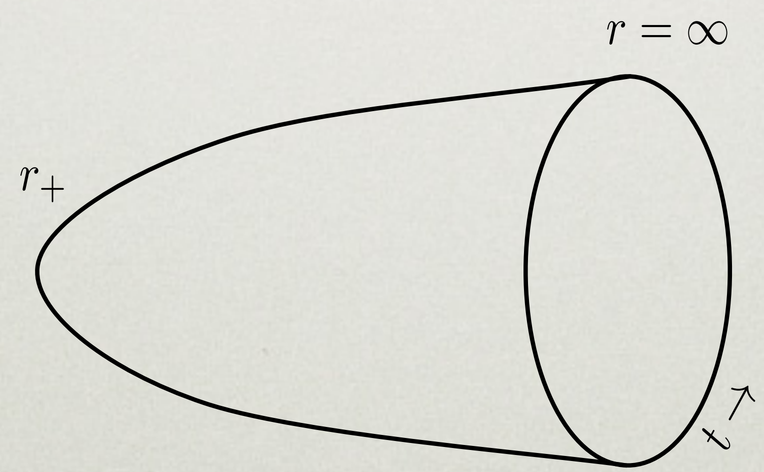
Contour plots in $\rho = \frac{z}{(z + \sqrt{1 - z})^2}$

Bulk Interpretation?

The Euclidean scalar BTZ metric is

$$ds^2 = (r^2 - r_+^2)dt^2 + \frac{dr^2}{r^2 - r_+^2} + r^2 d\theta^2$$

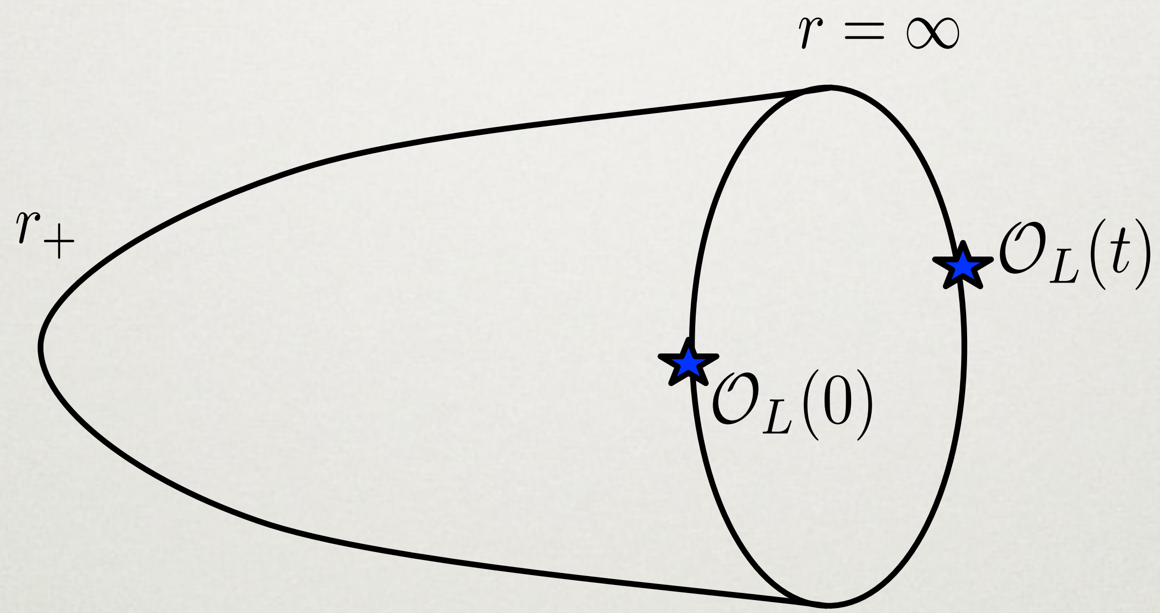
This corresponds to the "cigar geometry"



where periodicity in Euclidean time ensures the absence of a conical singularity at the horizon.

Euclidean Drama?

The cigar makes sense in the canonical ensemble



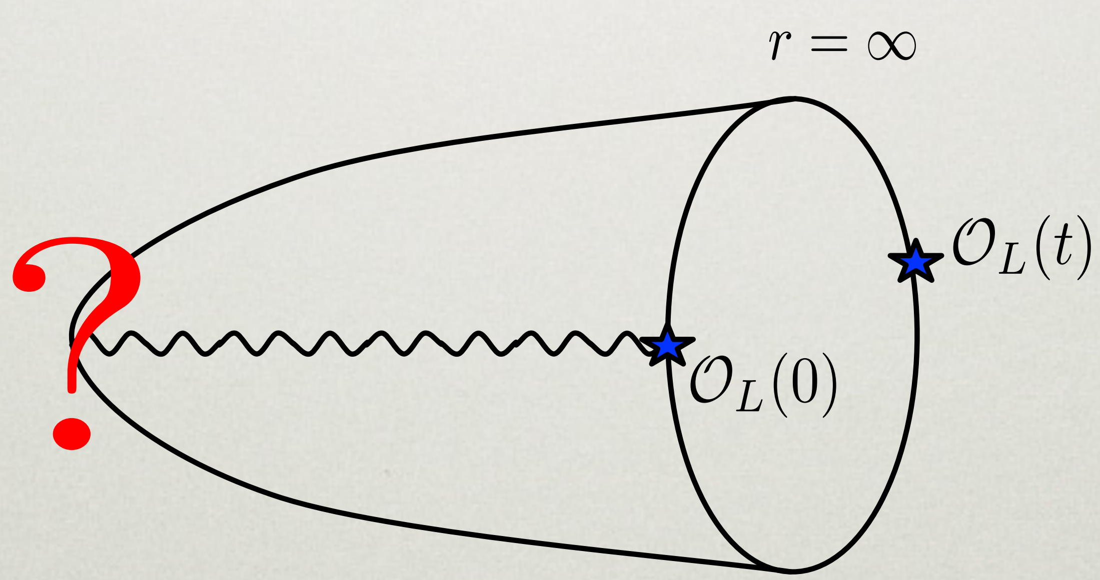
where correlators truly are periodic in Euclidean time.

But what geometric interpretation
should we attach to pure state black holes?

Euclidean Drama

Exact correlators in a pure state background may not be periodic… even approximately.

To place them on the cigar, we need a branch cut:



The correlators on the boundary can still be smooth, but they cannot be continued to the horizon!

Future Directions (in Progress)

Currently developing Virasoro-based tools for bulk reconstruction in order to probe the horizon.

1) How UV sensitive and theory-dependent is "Euclidean drama" near the horizon?

2) Does it infect Lorentzian observables?

3) Can we explicitly identify/quantify ambiguities?

Summary

I. Information loss in $\mathrm{AdS}_3/\mathrm{CFT}_2$ arises from the semiclassical expansion of Virasoro blocks

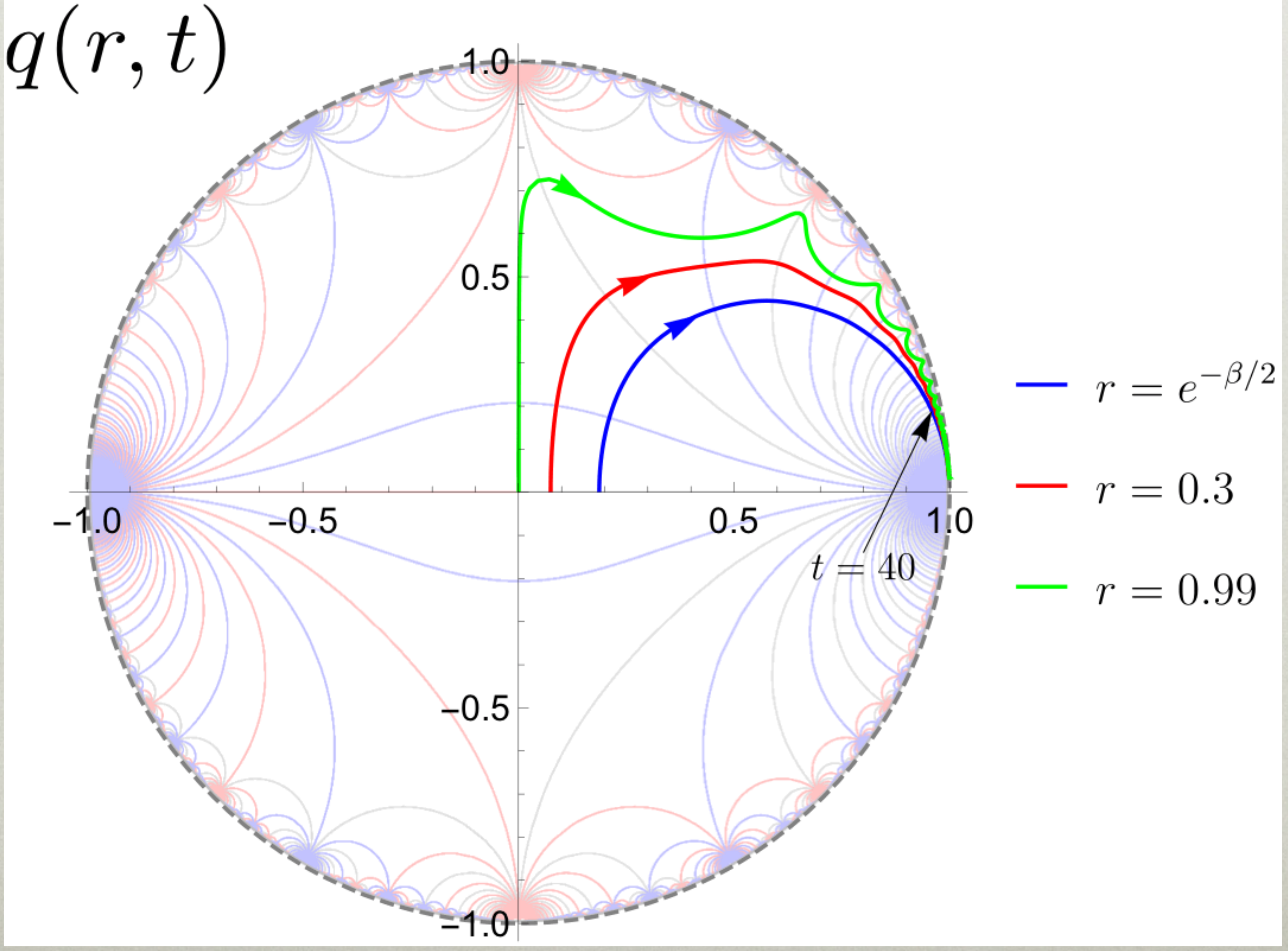
II. Many well-defined information loss problems are ameliorated or resolved by computable non-perturbative effects within Virasoro blocks

III. These non-perturbative effects have implications for bulk physics near the horizon!

Thank You!

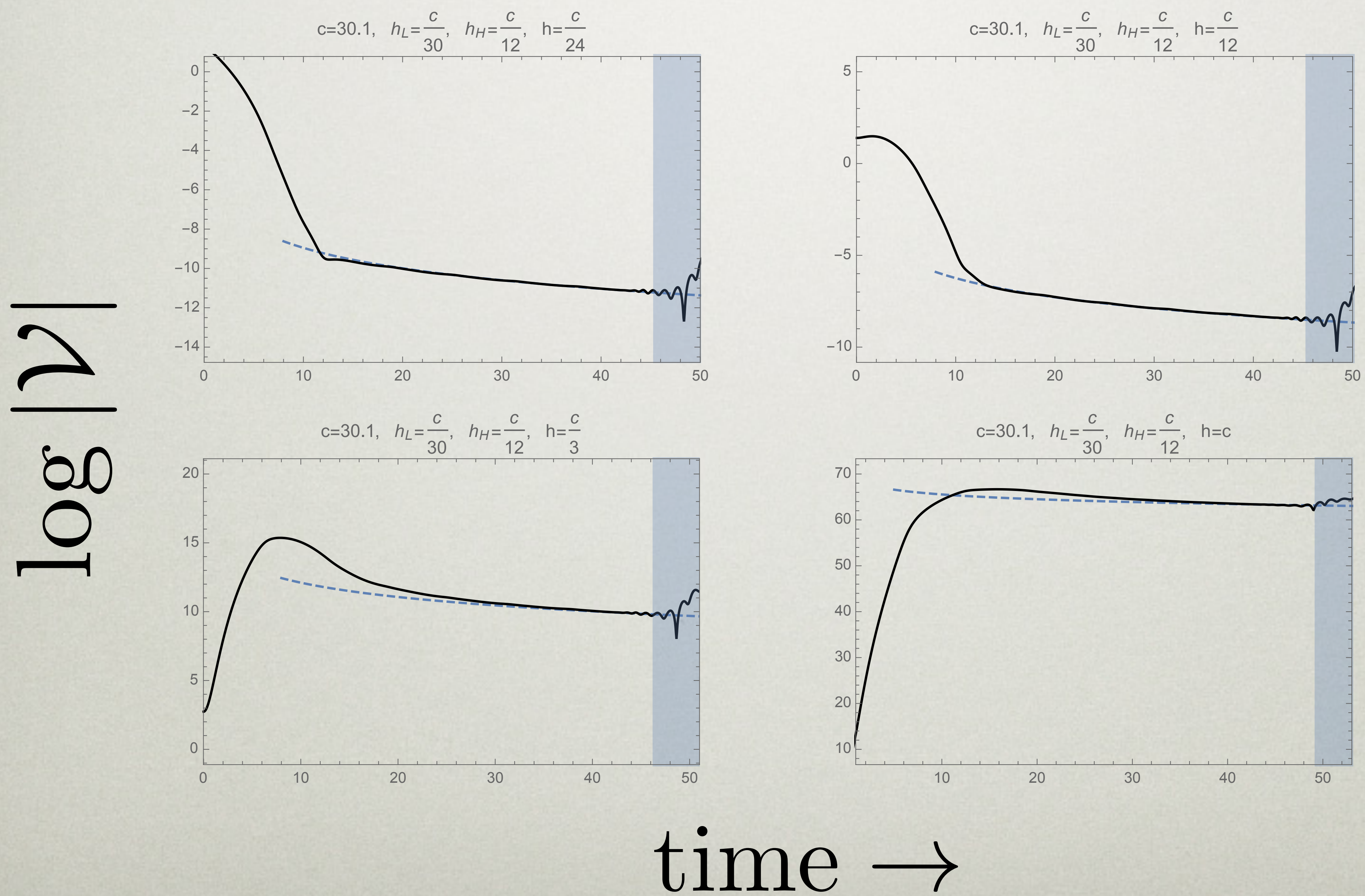
Extra Slides

Time Dependence of q



$$\langle \mathcal{O}_H(-\infty)\mathcal{O}_L(0)\mathcal{O}_L(t)\mathcal{O}_H(\infty)\rangle$$

Late-time $t^{-3/2}$ holds for non-vacuum blocks:



$$\langle \mathcal{O}_H(-\infty)\mathcal{O}_L(0)\mathcal{O}_L(t)\mathcal{O}_H(\infty)\rangle$$

We can even go to e^S time: