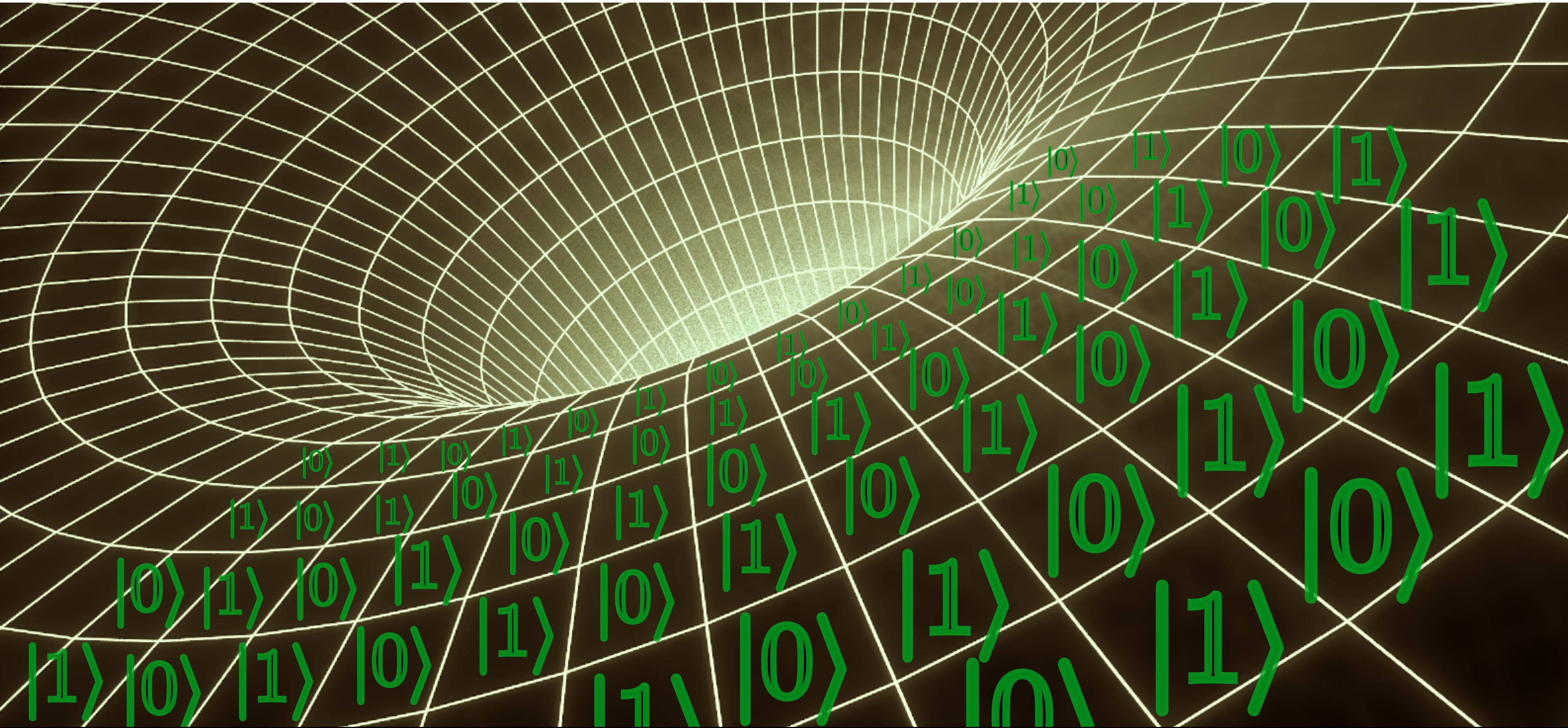
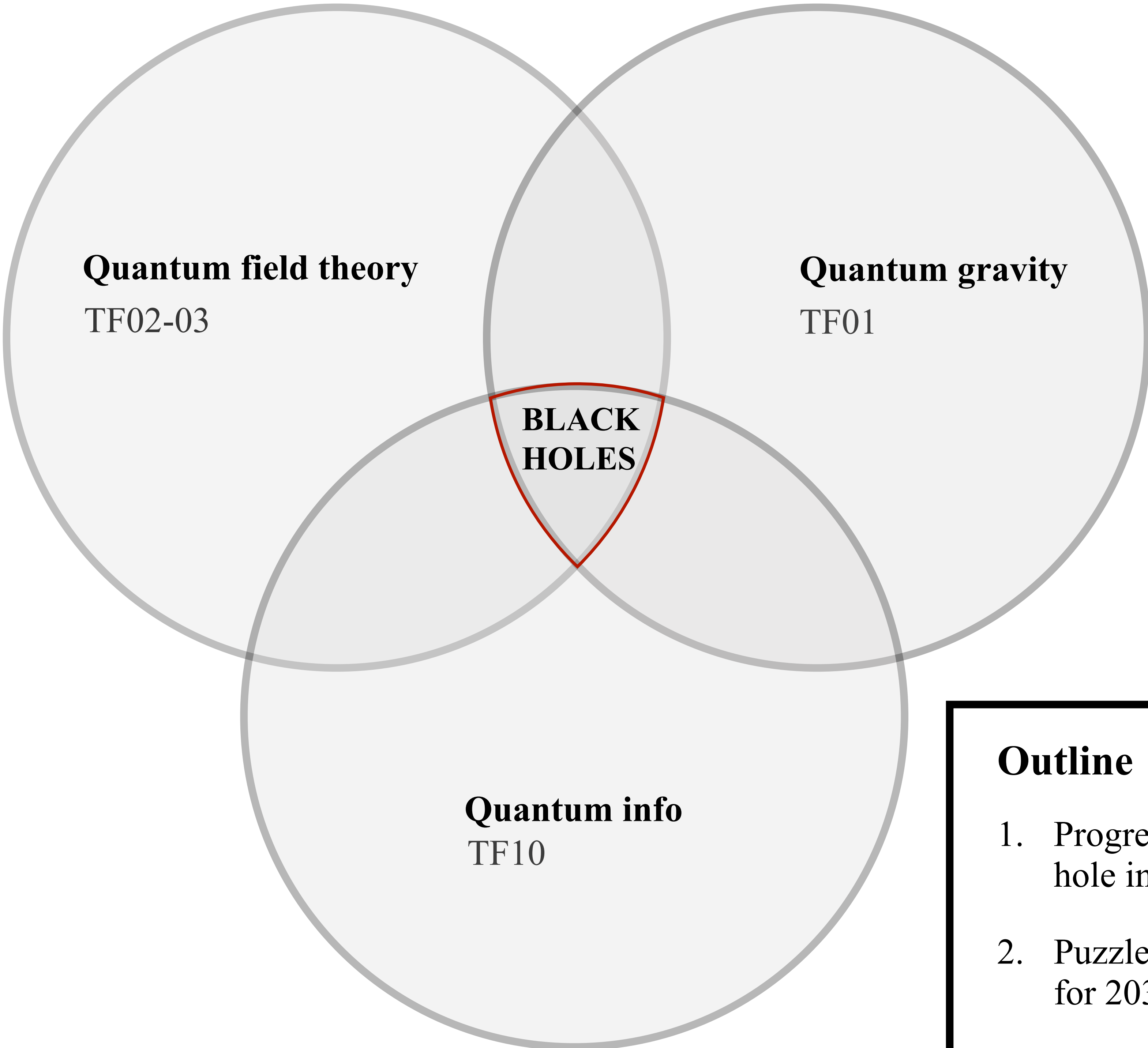


Black holes and quantum information

Tom Hartman
Cornell University

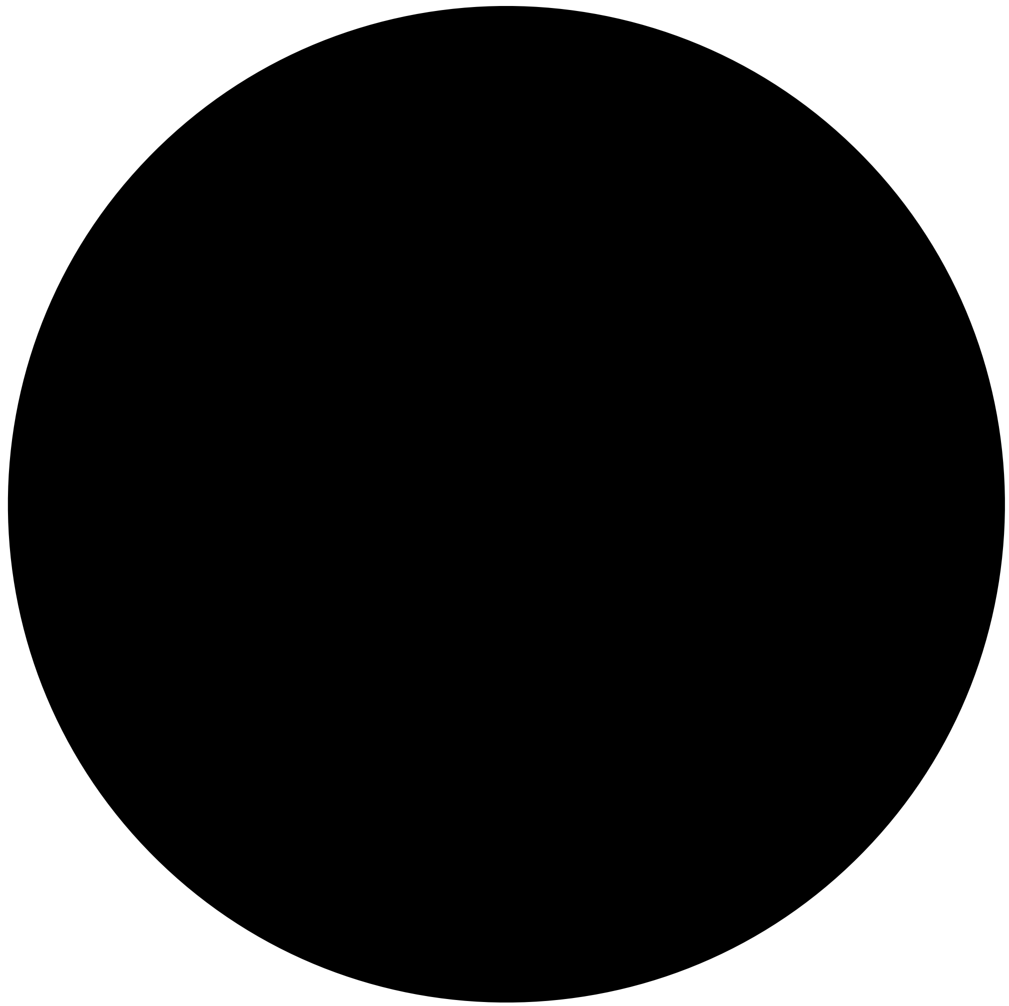
Snowmass 2021-2 ✦ KITP ✦ February 24, 2022



Outline

1. Progress on black hole information
2. Puzzles and targets for 2032

Classical black holes



are featureless objects — pure spacetime curvature

In quantum gravity,

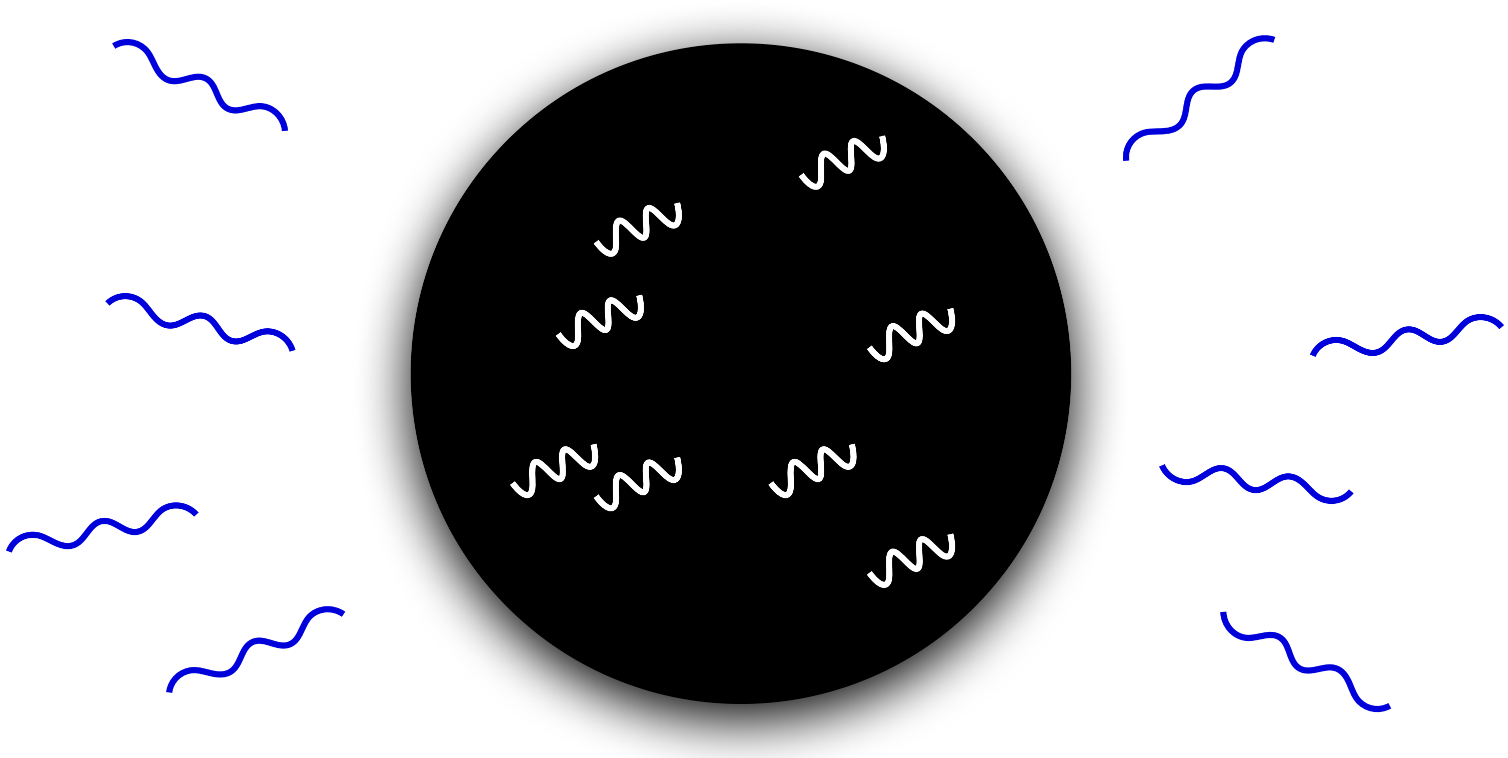
$$S = \frac{\text{Area}}{4G}$$

Where is this quantum information?

How is it encoded?

How does it escape when a black hole evaporates?

Black hole evaporation



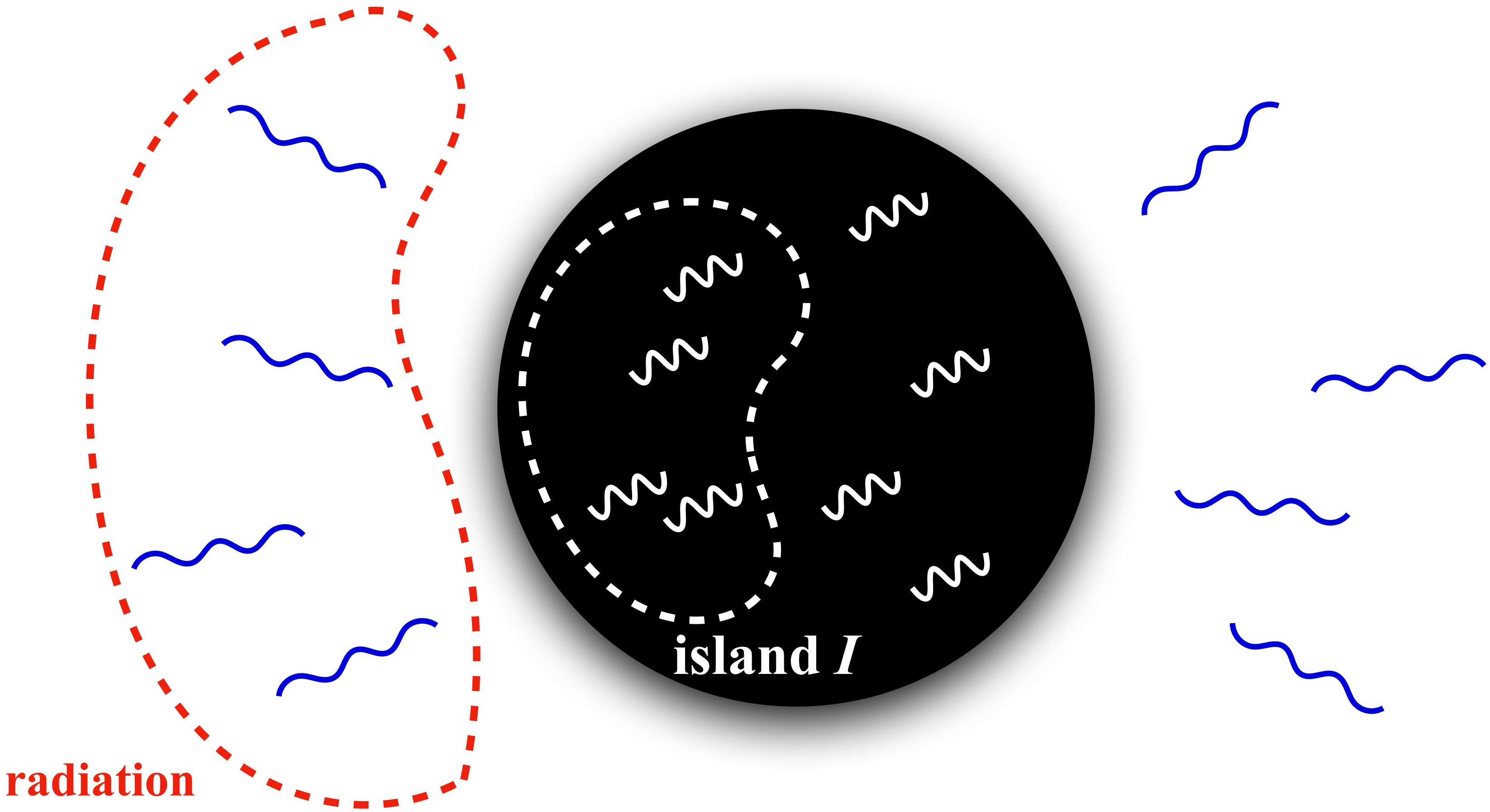
Hawking radiation is a process of *entanglement production* between the black hole interior and the radiation.

The “paradox” is that at the end, there is nothing for the radiation to be entangled with — QIS.

The Island Effect

[Penington, '19]
[Almheiri, Engelhardt, Marolf, Maxfield '19]

The Island Effect



Entropy formula: $S(\rho_{\rm rad}) = \min_I {\rm ext}_I \left[\frac{{\rm Area}(\partial I)}{4} + S_{\rm QFT}(I \cup {\rm rad}) \right]$

[Penington, '19]
[Almheiri, Engelhardt, Marolf, Maxfield '19]

Replica wormholes

A “replica wormhole” is a gravitational instanton supported by matter entanglement.

$\Longrightarrow$ island effect

Consider the "**purity**"

$$Z_2 := \mathrm{tr}\,(\rho^2)$$

pure: $Z_2 = 1$

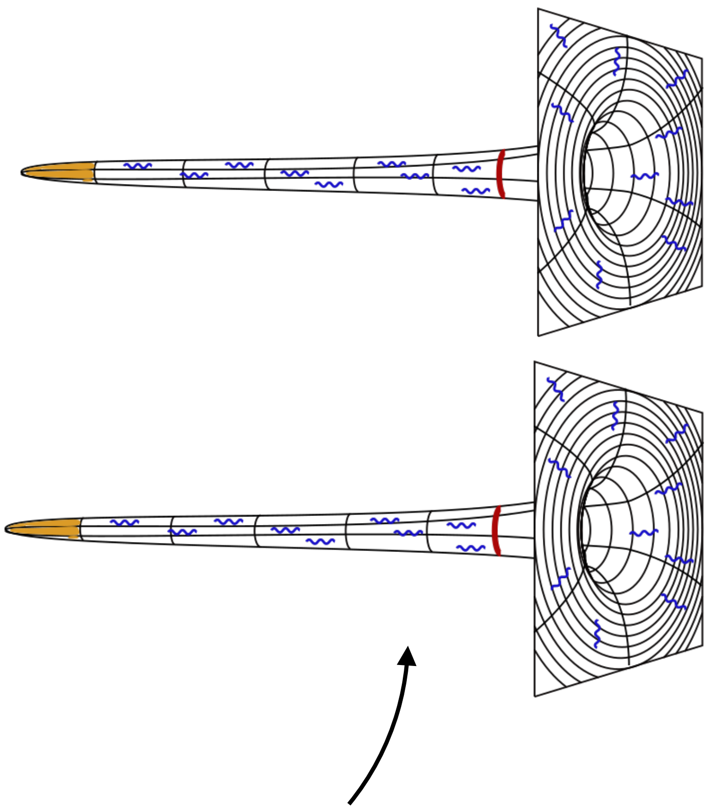
mixed: $Z_2 < 1$

[Almheiri, TH, Maldacena, Shaghoulian, Tajdini ’19]
[Penington, Shenker, Stanford, Yang ’19]

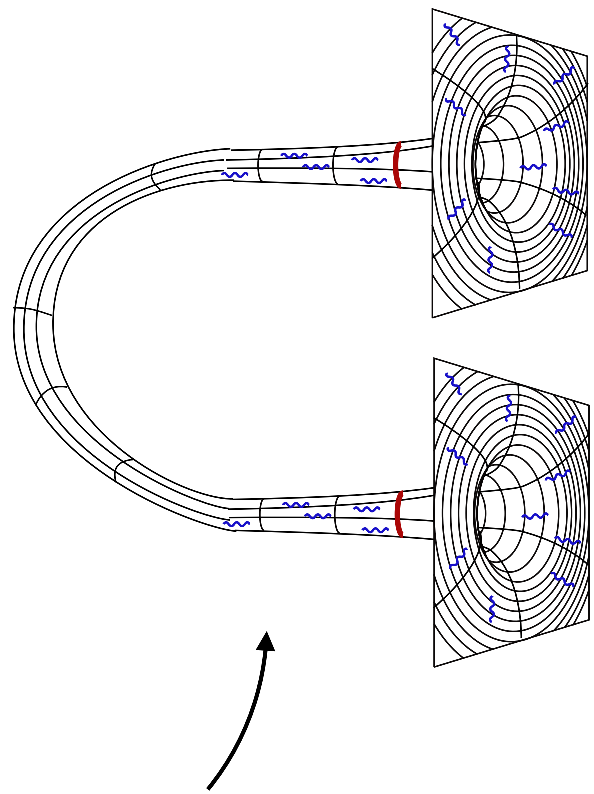
building on: [Lewkowycz, Maldacena ’13], [Dong, Lewkowycz, Rangamani ’16][Dong, Lewkowycz ’17]

Calculate the purity of the Hawking radiation by a gravitational path integral:

$$\mathrm{tr}(\rho^2) \approx$$



$$+$$

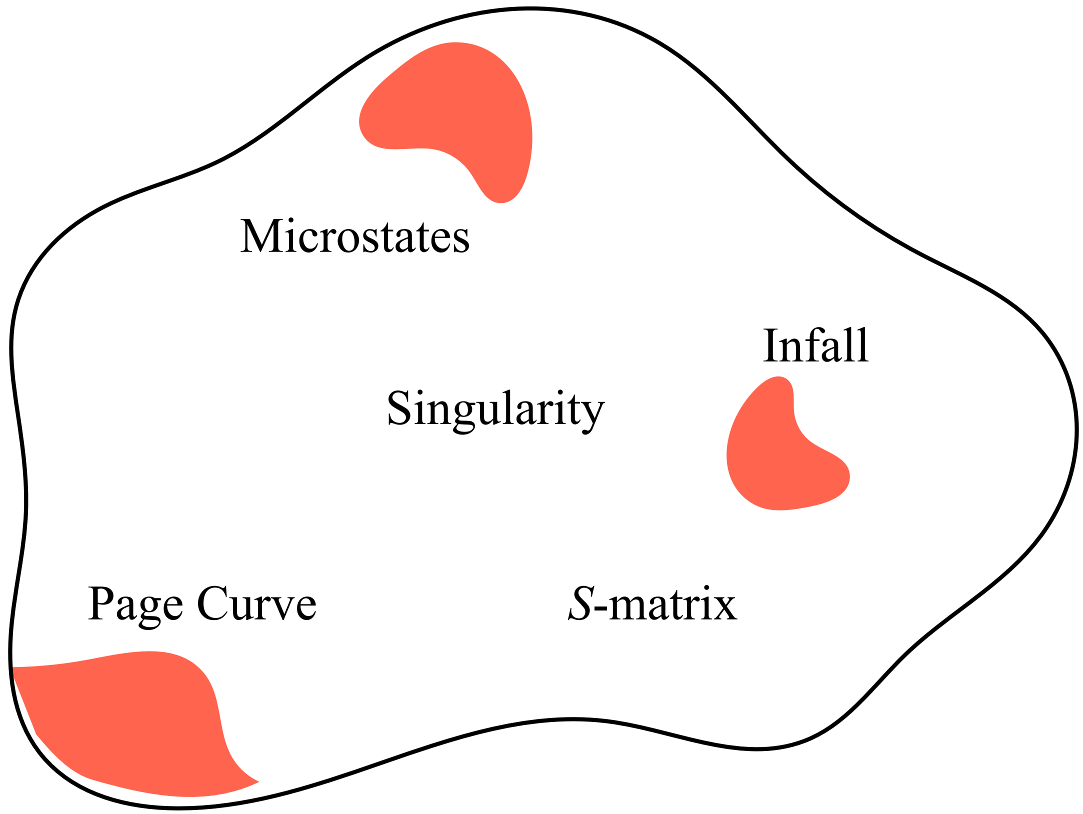


$$+ \cdots$$

Hawking radiation
is highly mixed

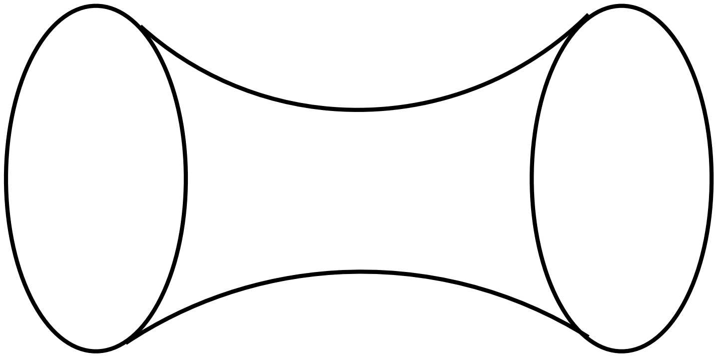
Island appears;
Hawking radiation re-purifies

Status of the information problem



Some corners have been solved; but the problem is now **BIGGER** than before!

More wormholes

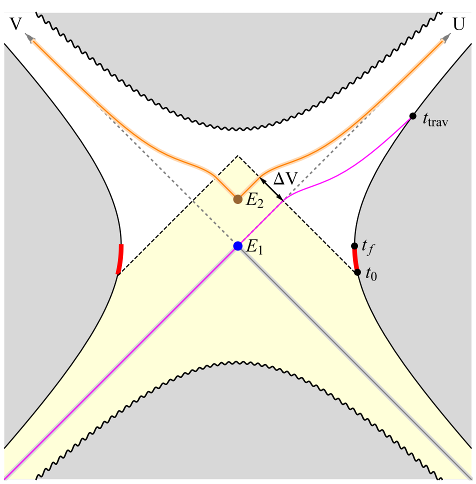


Double black holes

"Spectral form factor"

$$Z(\beta_1)Z(\beta_2)$$

[Cotler et al '16] [Saad, Shenker, Stanford '18-'19]
[Cotler and Jensen '19-'21]

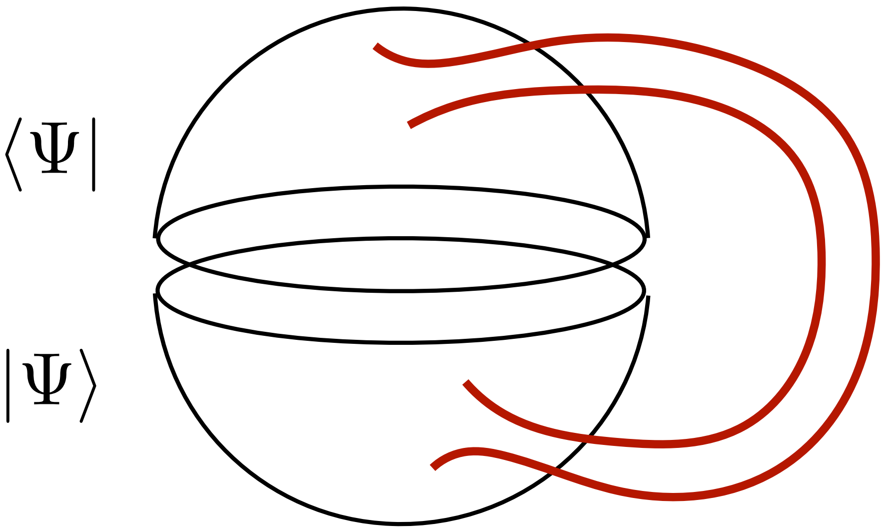


Traversable wormholes

$$S \to S + \int \mathcal{O}_1 \mathcal{O}_2$$

[Gao Jafferis Wall '16] [Maldacena Stanford Yang '17]
[Maldacena Qi '18] [Horowitz Marolf Santos Wang '19]

More wormholes

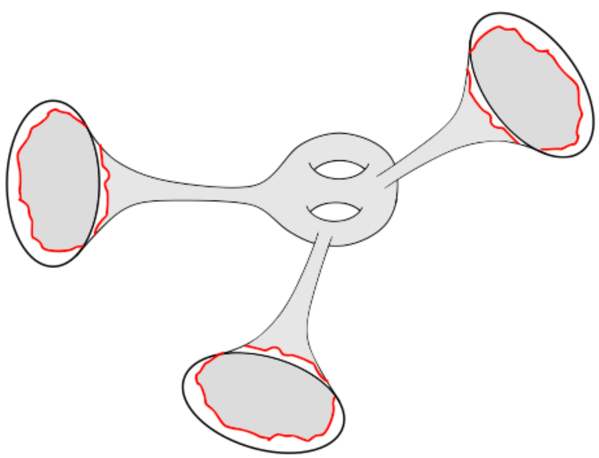


Bra-ket wormholes

States prepared by a gravitational path integral are not always as they seem.

Quantum cosmology revisited?

[Page '86] [Anous Kruthoff Mahajan '20]
[Chen Gorbenko Maldacena '20]



Et cetera.

cf. 1980's work by Giddings, Strominger, Polchinski, etc.

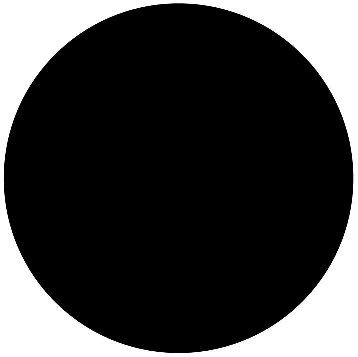
[Marolf Maxfield '20-'21] [Giddings Turiaci '20]

Three questions for 2032

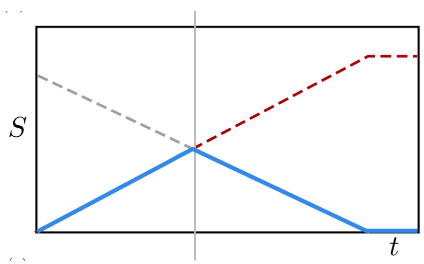
(This is just a representative sample; see white papers for more)

Question #1:

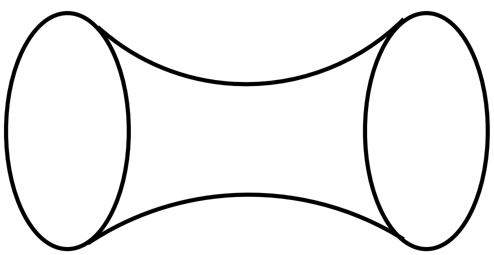
How much does low energy gravity know about the UV?



Black hole entropy $\Longrightarrow$ $\overline{\rho(E)}$



Island effect $\Longrightarrow$ $S(\rho_{\text{radiation}})$



Double black holes $\Longrightarrow$ $\overline{\rho(E)\rho(E')}$??

What else?

Question #2:

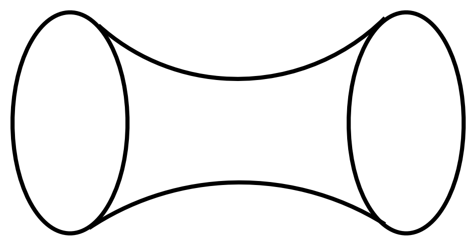
What is the role of averaging in *d > 2* gravity and in QFT?

2d gravity is holographically dual to random matrix theory

[Saad, Shenker, Stanford '19]

This is not ordinary quantum mechanics!

Factorization puzzles:



What about $d > 2$? There are many hints that averaging is useful.

Double cone geometry [Saad, Shenker, Stanford '18] etc.

Toy models in 3d gravity [Maloney Witten '20] [Afkhami-Jeddi Cohn Hartman Tajdini '20]

Spectral analysis in SYM [Collier Perlmutter '22]

Presumably, UV-complete theories of gravity do not have any intrinsic averaging.

A tentative picture is that in realistic theories of gravity,

$$\sum \left(\begin{array}{c} \text{Boundary} \\ \text{instantons} \end{array} \right) = \sum \left(\begin{array}{c} \text{Bulk} \\ \text{instantons} \end{array} \right) \approx \sum \left(\begin{array}{c} \text{Bulk} \\ \text{topologies} \end{array} \right)$$

Cf. [Eberhardt '20-21]

Is this correct?

Averaging and the conformal bootstrap

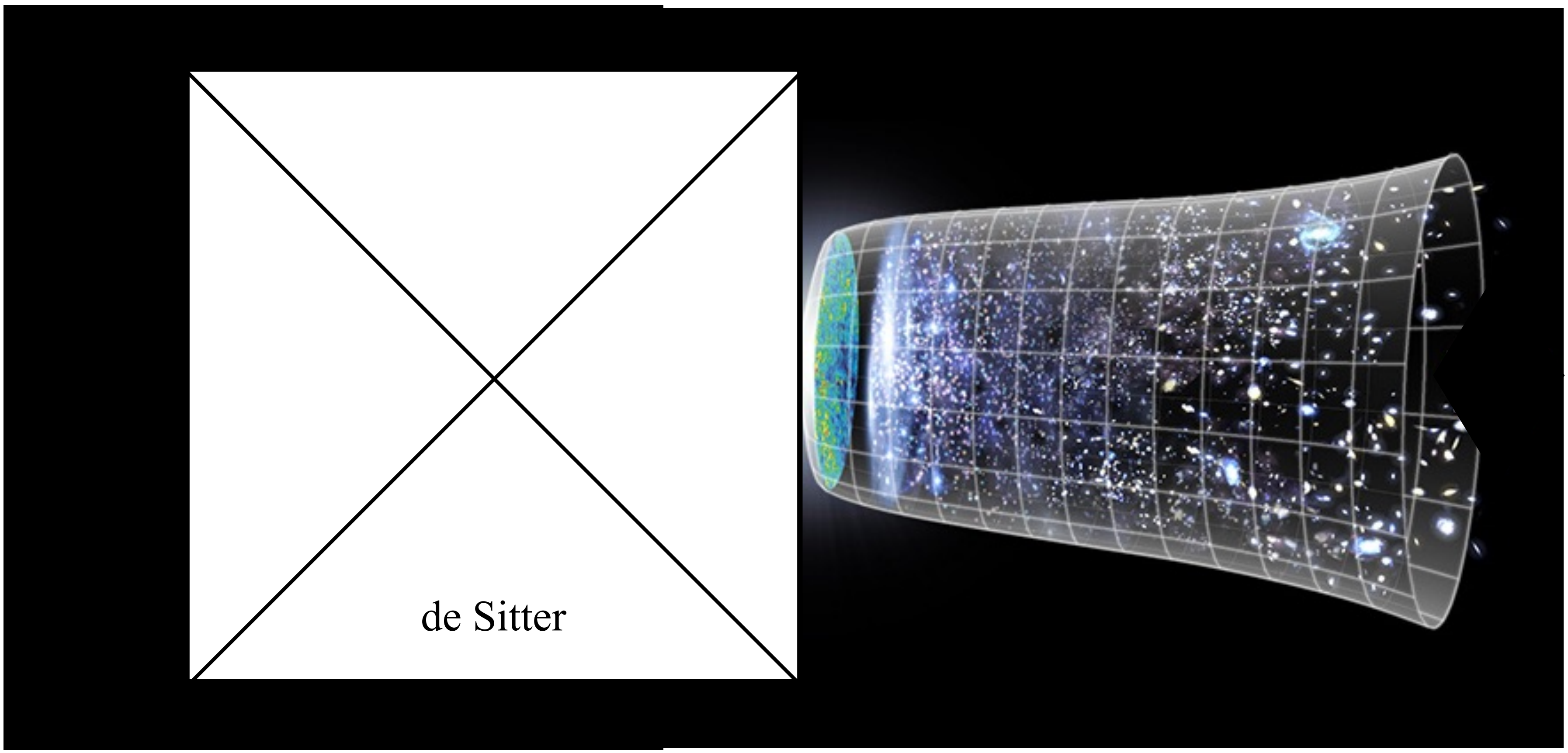
There is a mini-industry of matching gravity to bootstrap calculations, most of it pre-2018.

e.g. [Heemskerk, Penedones, Polchinski, Sully '09]

Where are the wormholes???
Statistics of CFT Data?

Question #3:

What is the role of quantum information and higher topology in cosmology?



White papers

TF01	"Quantum aspects of black holes and emergent spacetime," with Bousso, Dong, Engelhardt, Faulkner, Shenker, and Stanford.
TF03	"The analytic conformal bootstrap," with Mazac, Simmons-Duffin, and Zhiboedov.
TF10	"Quantum information in QFT and quantum gravity," with Faulkner, Headrick, Rangamani, and Swingle.

Thank you.