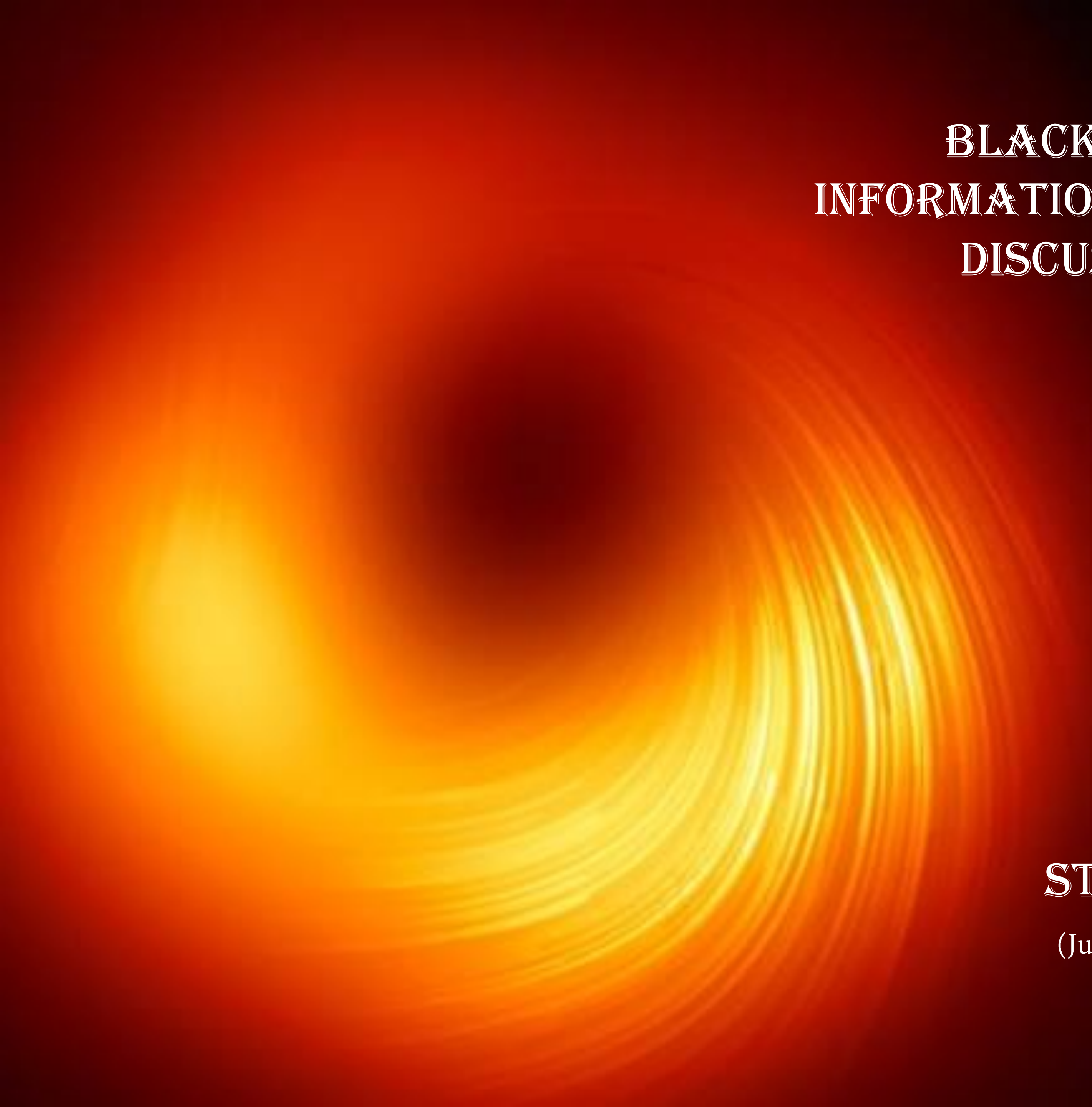
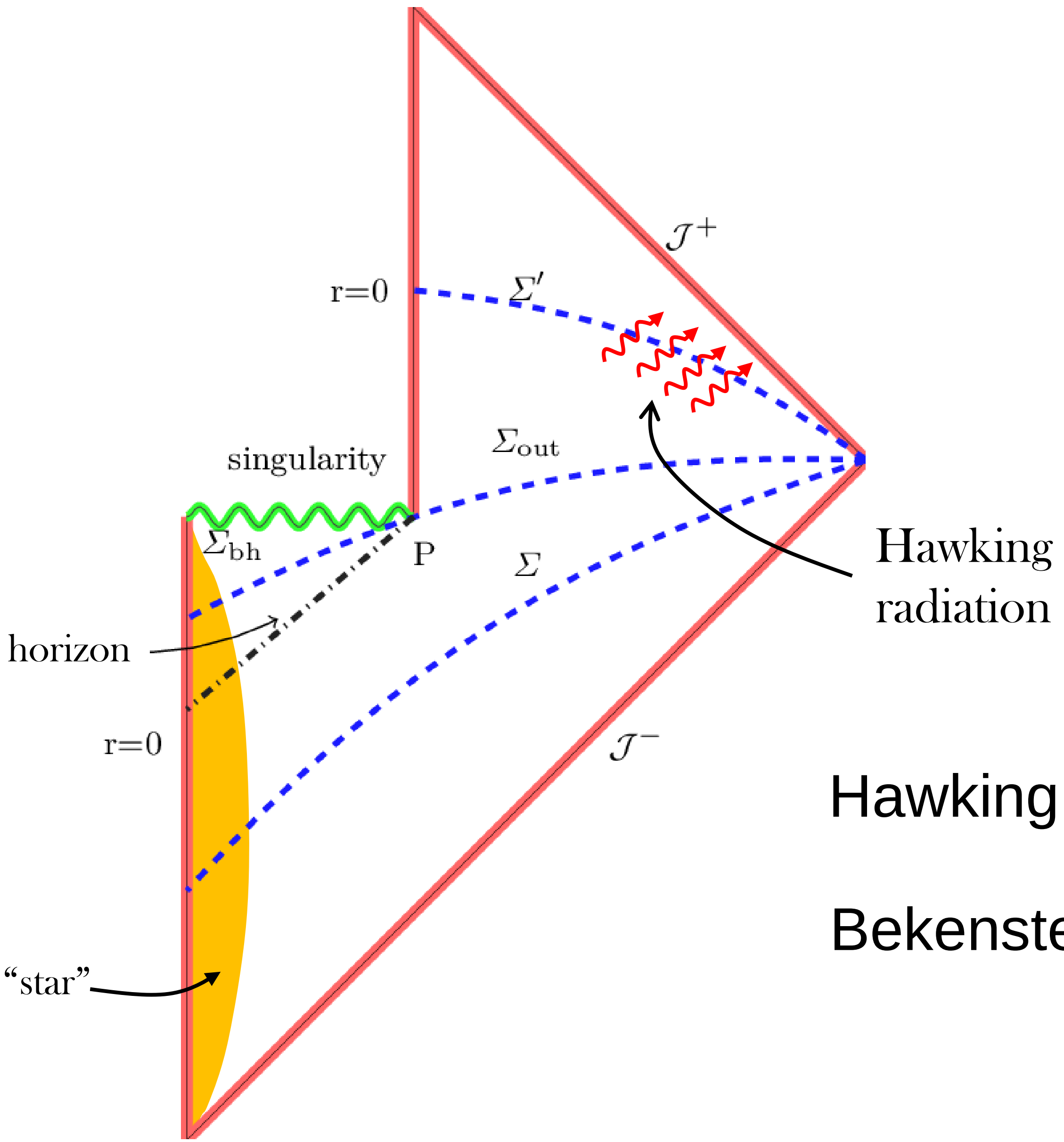


BLACK HOLE INFORMATION PARADOX DISCUSSION

STRINGS 2021

(June 21 – July 2, 2021)

Black hole information paradox:



Hawking temperature: $T = \dfrac{\hbar\kappa}{2\pi}$

Bekenstein-Hawking entropy:

$$S_{BH} = \frac{A_{horiz}}{4\,G_N\,\hbar}$$

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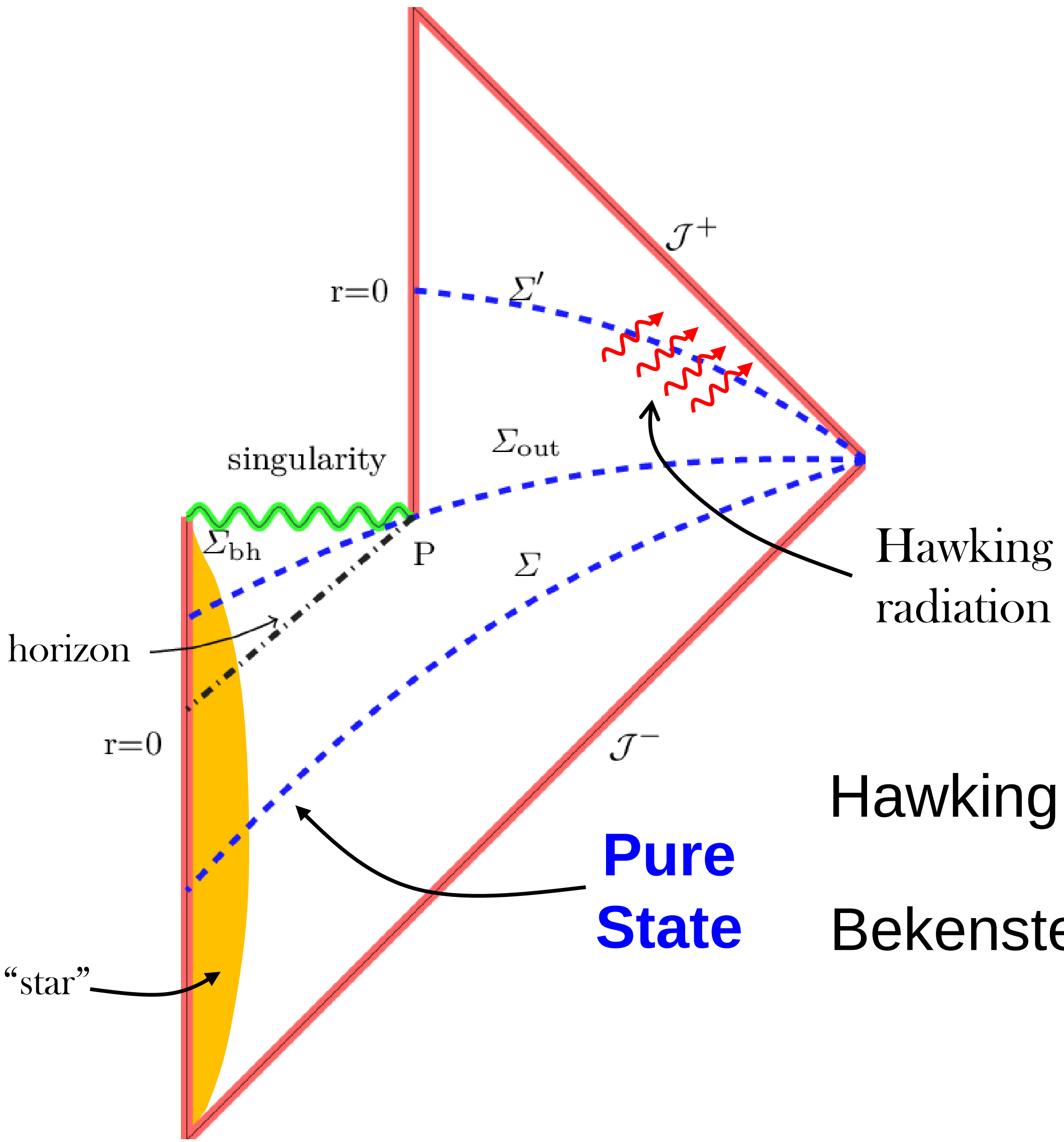

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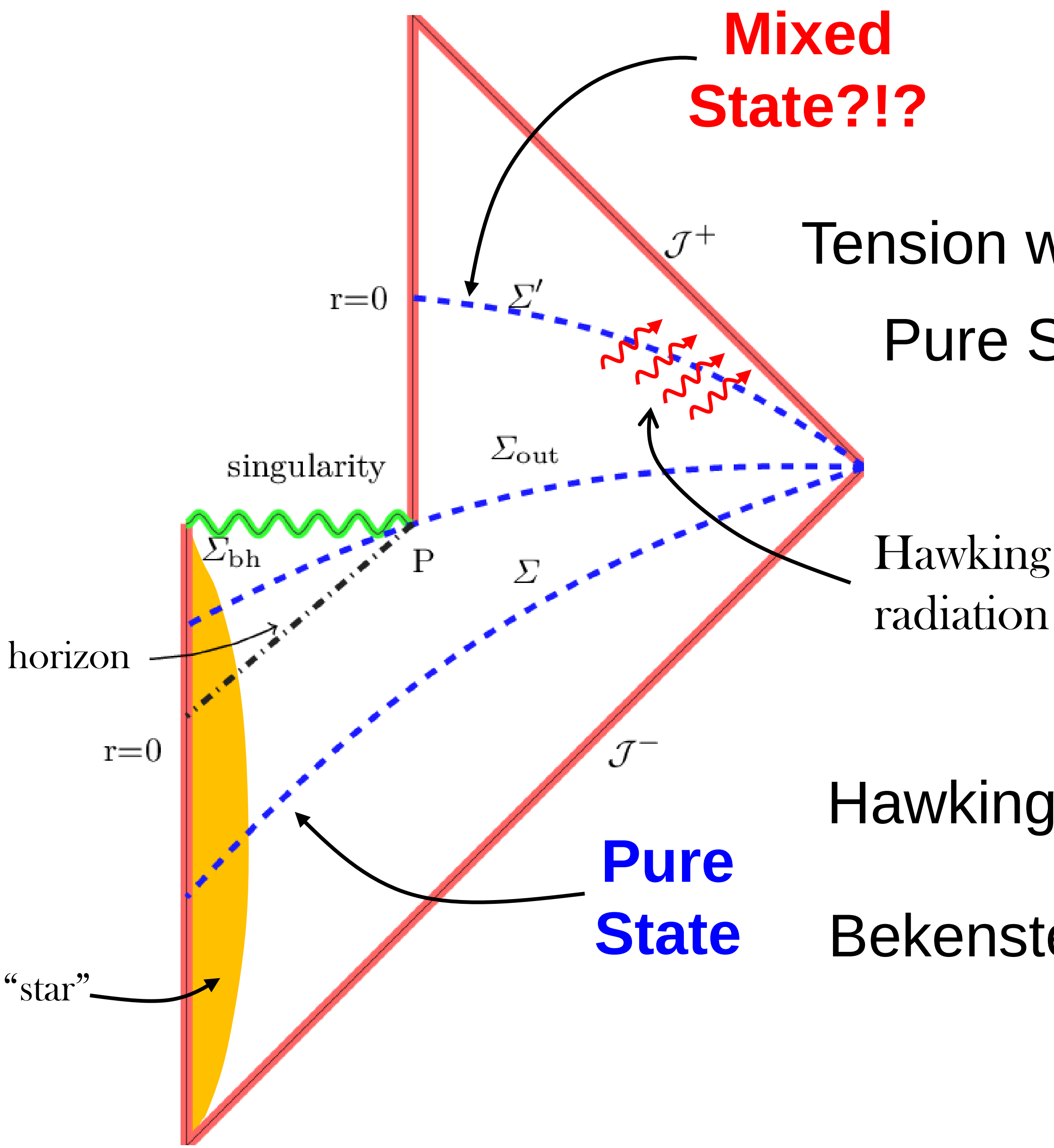

Tension with Unitary Time Evolution:

Pure State ⇏ Mixed State

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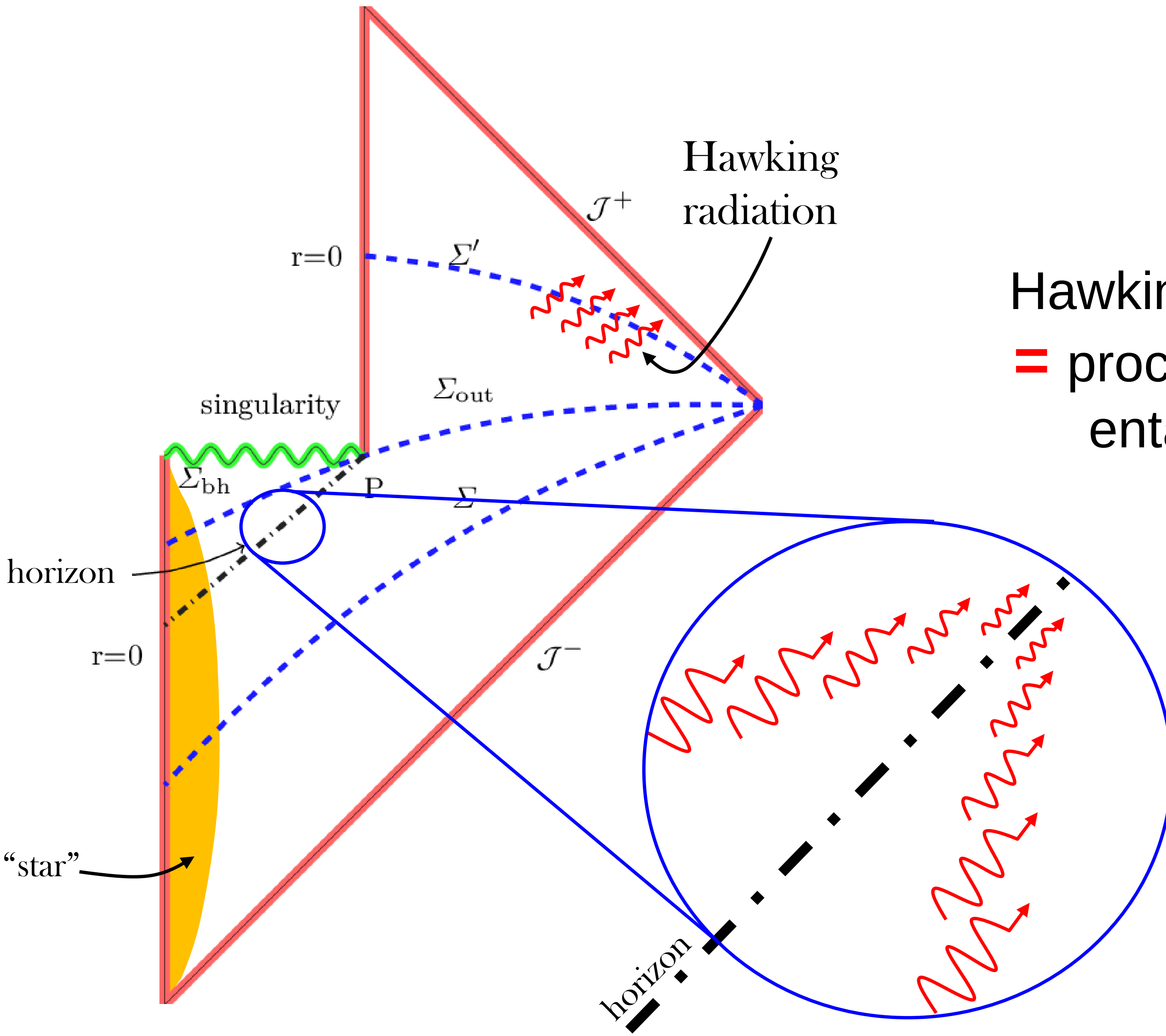
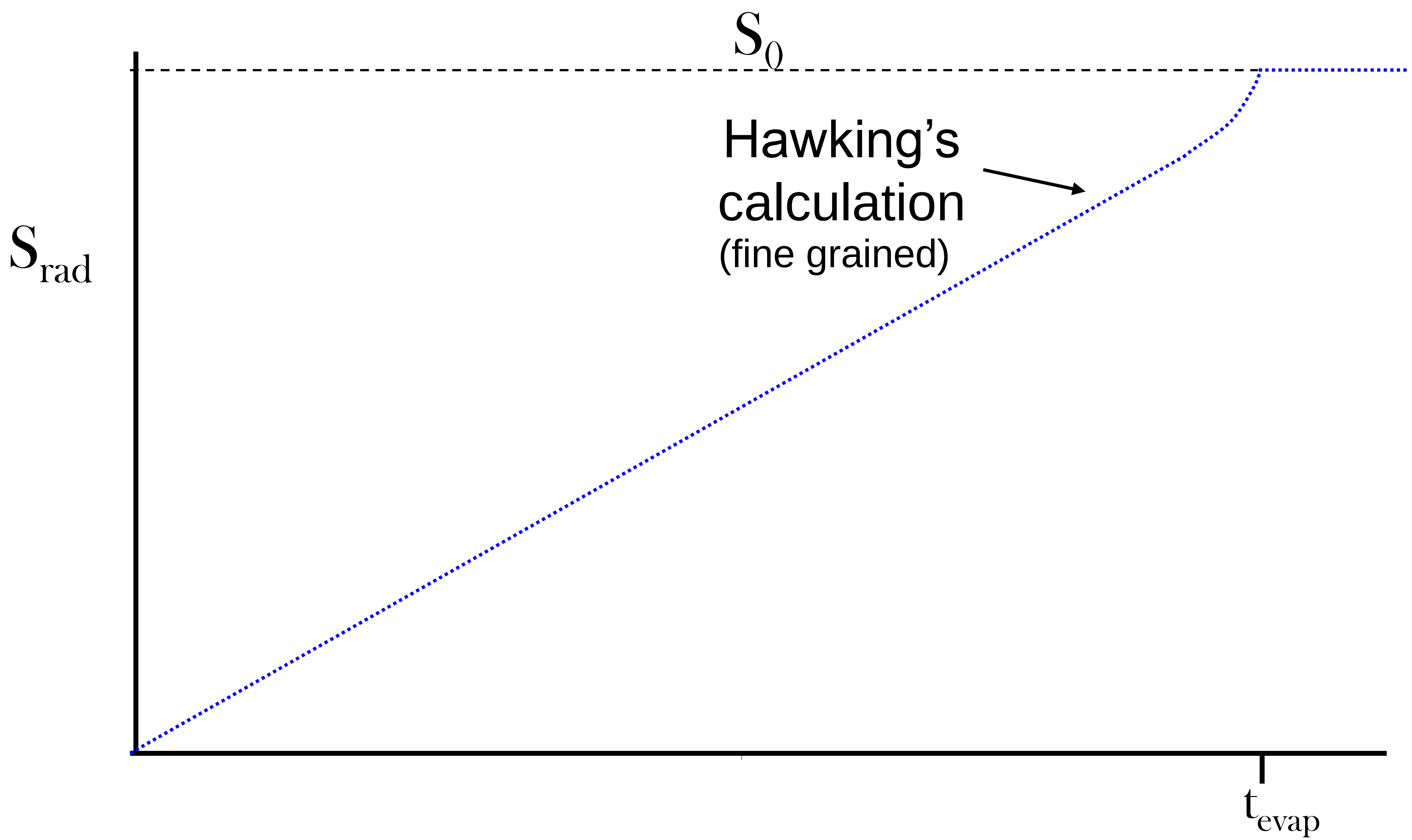


Hawking evaporation
= process producing entanglement

Page Curve: unitarity requires radiation entropy bounded by BH entropy $S_{rad} \leq S_{BH}$



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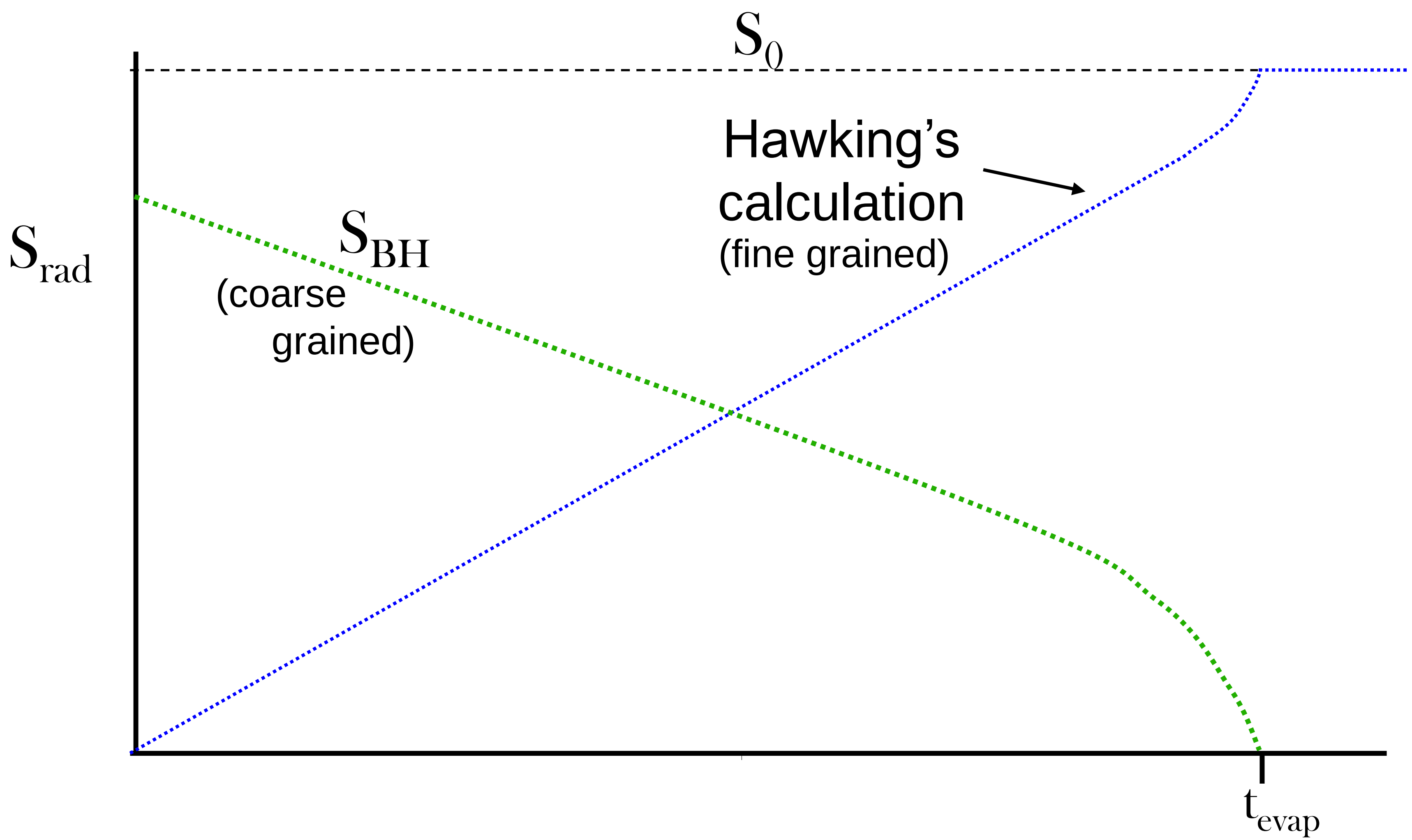

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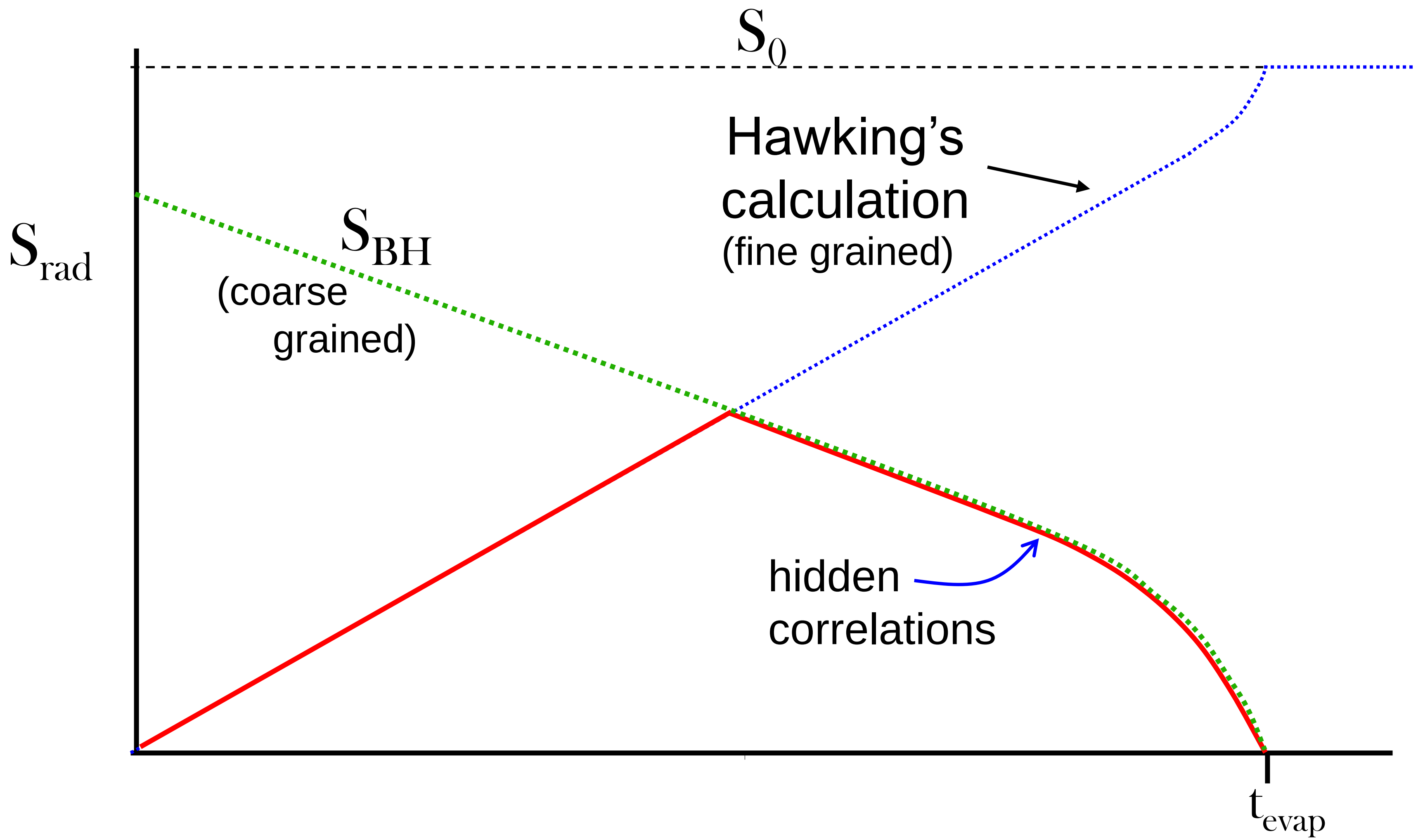

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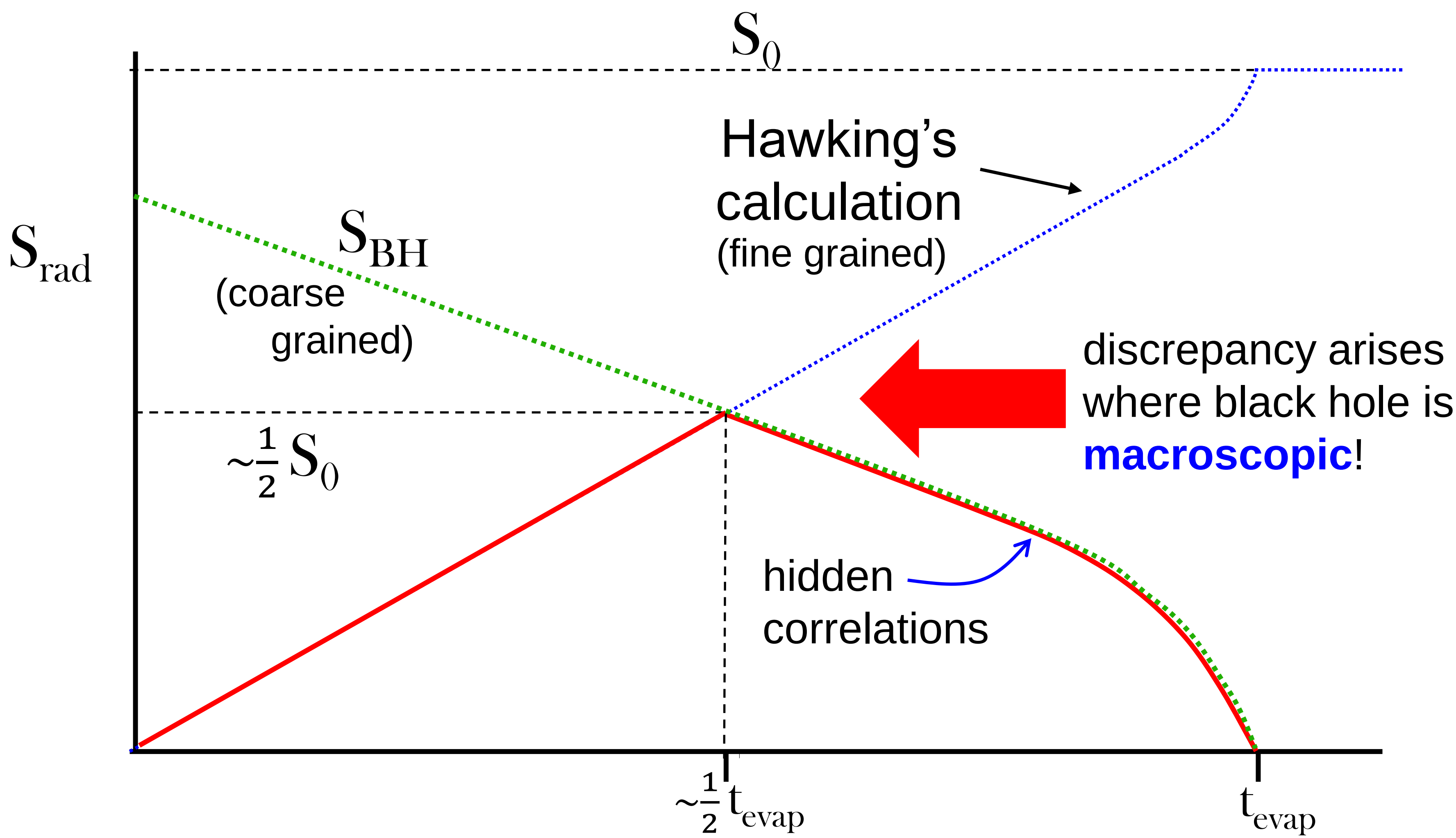

not corrected by small modifications of Hamiltonian or state near the horizon

Mathur; Almheiri, Marolf, Polchinski & Sully

New insight:

- with recent progress, it is possible to compute the Page curve in a controlled manner!

Penington [arXiv:1905.08255]
Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]

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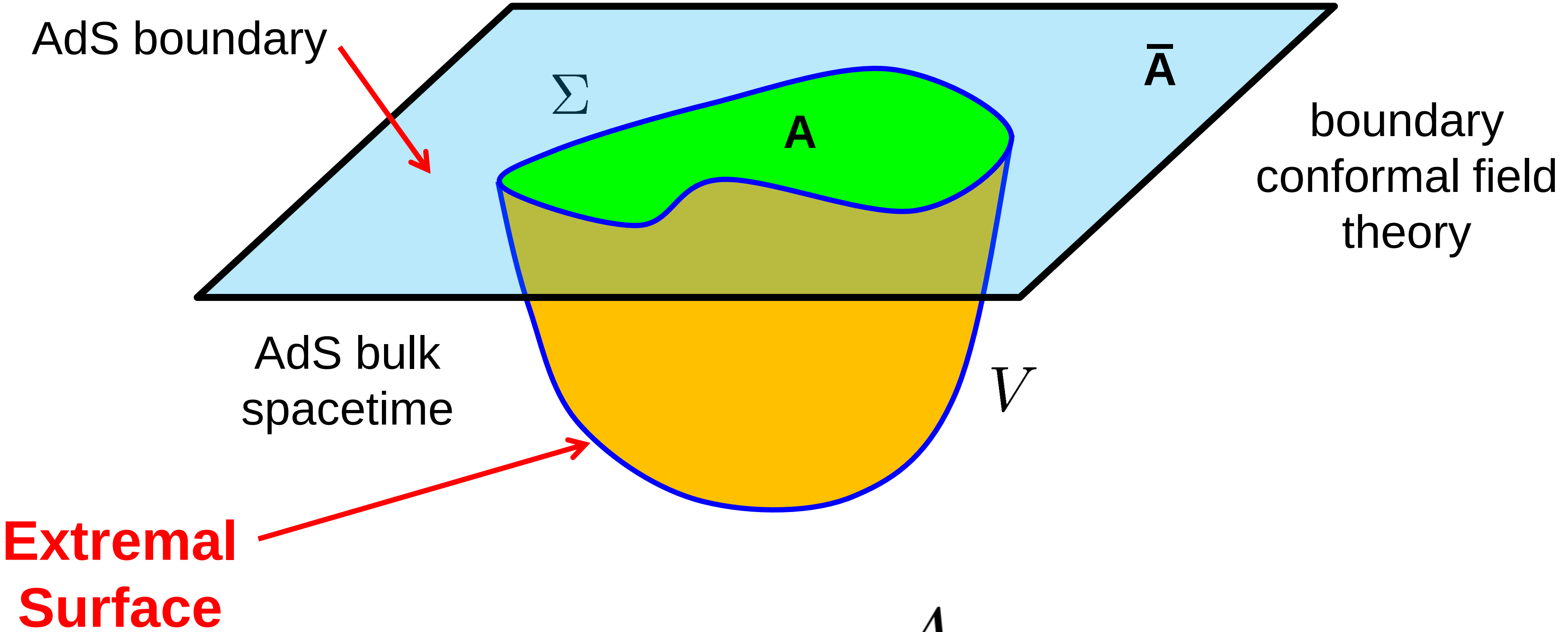
(Almheiri, Mahajan, Maldacena, Zhao, Akers, Harlow, Rozali, Raamsdonk, Sully, Wadell, Wakeham,Nomura, Moitra, Sake, Trivedi, Vishal, Akers, Engelhardt, Harlow, Chen, Fisher, Hernadez, Ruan, Bousso, Tomasevic, Almheiri, Mahajan, Santos, Penington, Shenker, Stanford, Yang, Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, Blommaert, Mertens, Verschelde, Chen, Qi, Zhang, Verlinde, Kim, Tang, Preskill, Balasubramanian, Kar, Parrikar, Sárosi, Ugajin, Piroli, Sünderhauf, Qi, Marolf, Maxfield, Liu, Vardhan, Pollack, Rozali, Sully, Wakeham, Agarwal, Bao, Akers, Engelhardt, Penington, Usatyuk, Chen, Zhao, Brown, Gharibyan, Penington, Susskind, Chen, Myers, Neuenfeld, Reyes, Sandor, Banks, Alishahiha, Astaneh, Naseh, Krishnan, Patil, Pereira, Agón, Lokhande, Pedraza, Hollowood, Kumar, Hartman, Shaghoulian, Strominger, Fitkevich, Levkov, Zenkevich, Sully, Raamsdonk, Wakeham, Zhang, Hashimoto, Iizuka, Matsuo, Jana, Loganayagam, Rangamani, Giddings, Turiaci, Anegawa, Iizuka, Bhattacharya, Gautason, Schneiderbauer, Sybesma, Thorlacius, Chen, Gorbenko, Maldacena, Gomez, Karlsson, Krishnan, Engelhardt, Fischetti, Maloney, Hollowood, Kumar, Legramandi, Dong, Qi, Shangnan, Yang, Anous, Kruthoff, Mahajan, Bousso, Wildenhain, Bak, Kim, Yi, Yoon, Chandrasekaran, Miyaji, Rath, Li, Chu, Zhou, Geng, Karch, Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, ...)

Key Ingredient: RT ➡ Quantum Extremal Surfaces



$$S(A) = \underset{\partial V \sim \Sigma}{\text{ext}} \frac{A_V}{4G_N}$$

(Ryu & Takayanagi; Hubeny, Rangamani & Takayanagi; Lewkowycz & Maldacena; . . . .)

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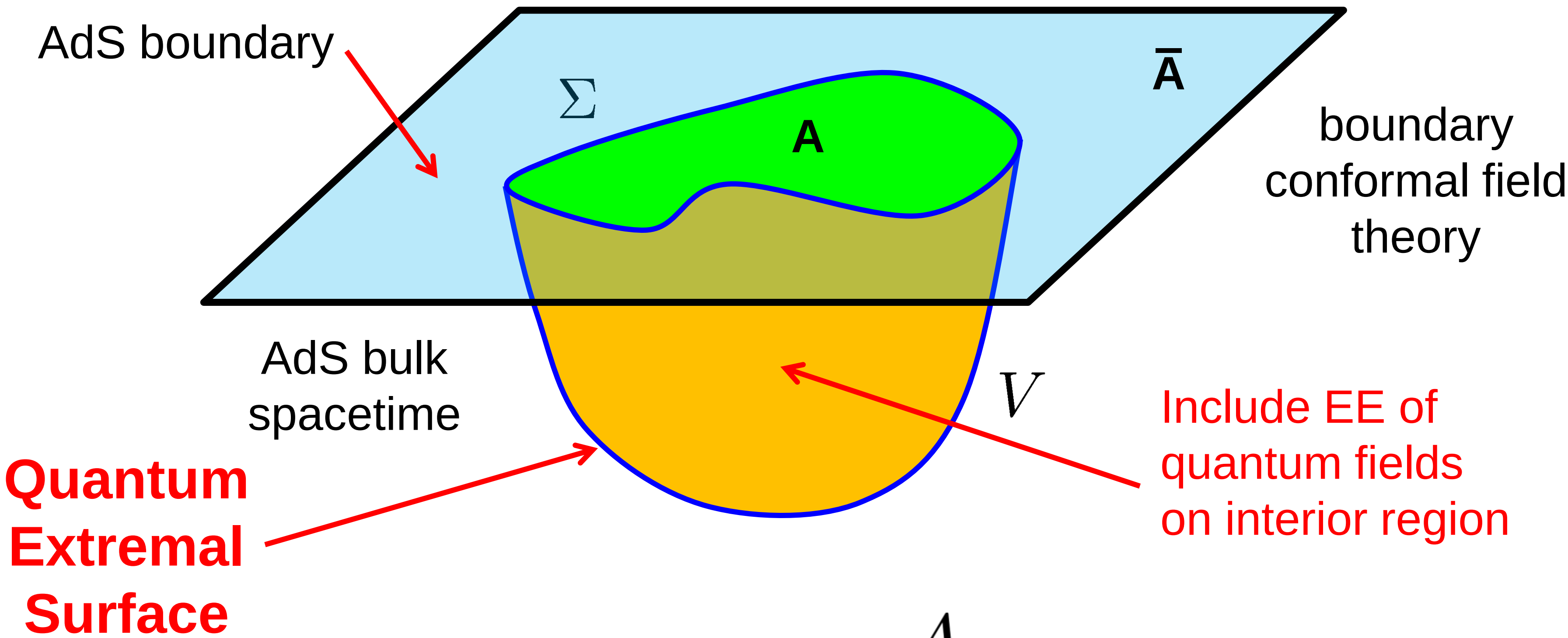

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(Ryu & Takayanagi; Hubeny, Rangamani & Takayanagi; Lewkowycz & Maldacena; . . . .)

$$S(A) = \operatorname*{ext}_{\partial V \sim \Sigma} \left[\frac{A_V}{4G_N} + S_{QFT}(\Sigma) \right]$$

(Faulkner, Lewkowycz & Maldacena; Engelhardt & Wall)

Almheiri, Mahajan, Maldacena & Zhao

➡ Island Rule:

- entropy of the Hawking radiation is given by

$$S_{EE}(\mathbf{R}) = \min \left\{ \underset{\text{islands}}{\text{ext}} \left(S_{QFT}(\mathbf{R} \cup \text{islands}) + \frac{A(\partial(\text{islands}))}{4G_N} \right) \right\}$$

→ evaluate the generalized entropy of radiation region **R** combined with various space-like subregions in the gravitating region, ie, islands

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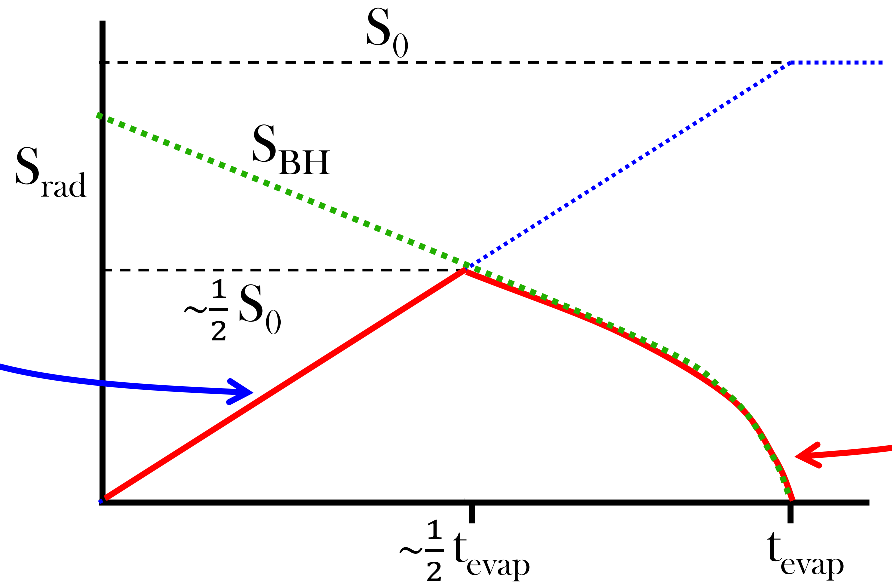
Early: island is the empty set; agrees with Hawking's calculation

Late: large entanglement between radiation and region behind horizon; **new saddle** with nontrivial island



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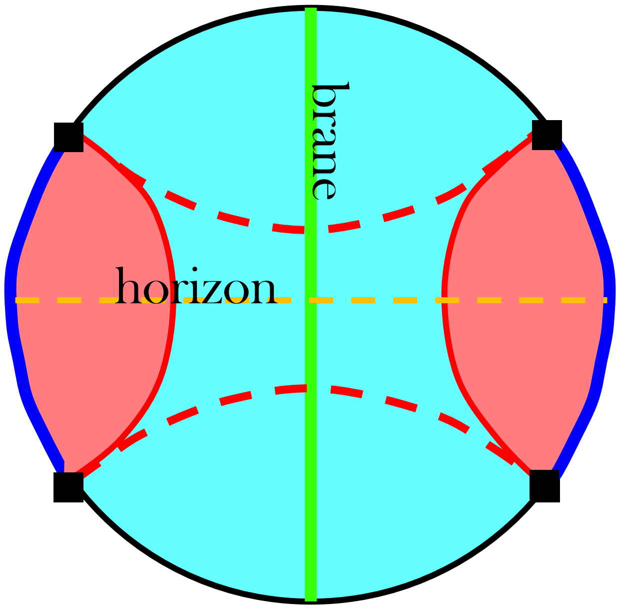
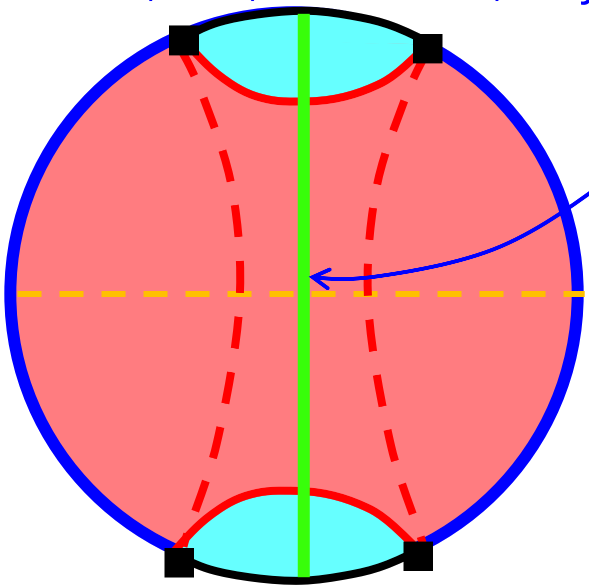
→ evaluate the generalized entropy of radiation region **R** combined with various space-like subregions in the gravitating region, ie, islands

- competition of saddles, eg, doubly holographic models

Sully, Raamsdonk & Wakeham
Chen, RM, Neuenfeld, Reyes & Sandor





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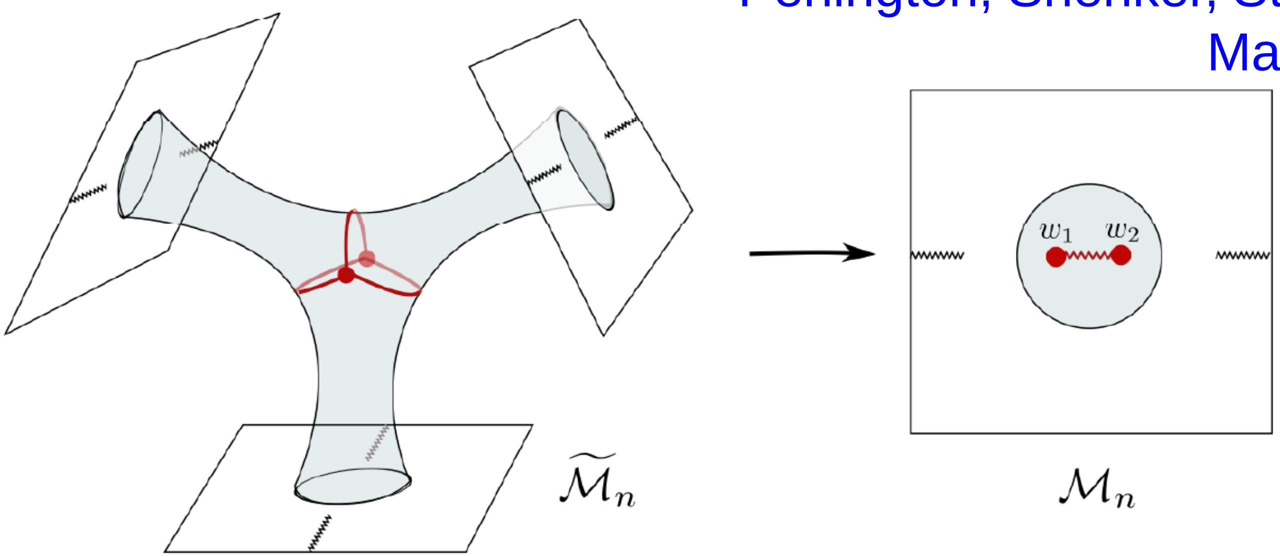
- justified by replica wormhole calculations (Shenker review)

Almheiri, Hartman, Maldacena, Shaghoulian & Tajdini
Penington, Shenker, Stanford & Yang
Maxfield & Marolf



BEYOND ENTROPY

COMPLEXITY IN THE INFORMATION PARADOX

Status check:

Done: derived the Page curve!

Not done: resolved the information paradox.

Entropy is not enough?™ (Susskind)

Harlow-Hayden: Decoding the Hawking radiation is exponentially complex because it requires conditioning on an outcome (postselection). Followed by Aaronson and clarified and developed further by Kim-Tang-Preskill.

COMPLEXITY IN THE INFORMATION PARADOX

Any full resolution of the paradox would need to explain how to compute the Page curve from first principles, and consequently also explain what Hawking missed.

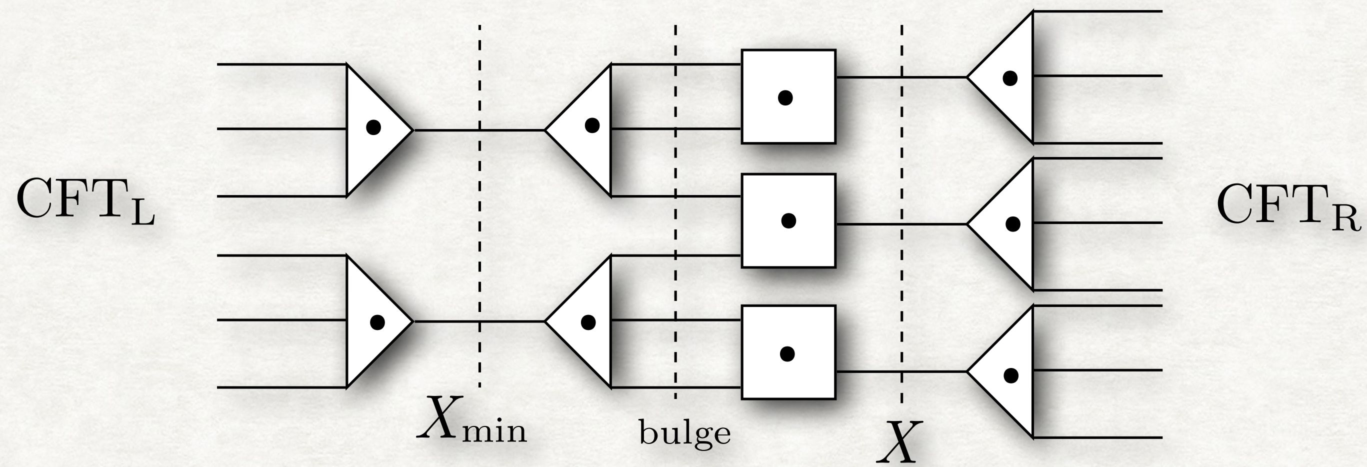
Comment: seems that the *production* of exponential complexity is a critical aspect of the information problem, and the ability to *access* exponentially complex operators appears to be crucial in deriving unitarity.

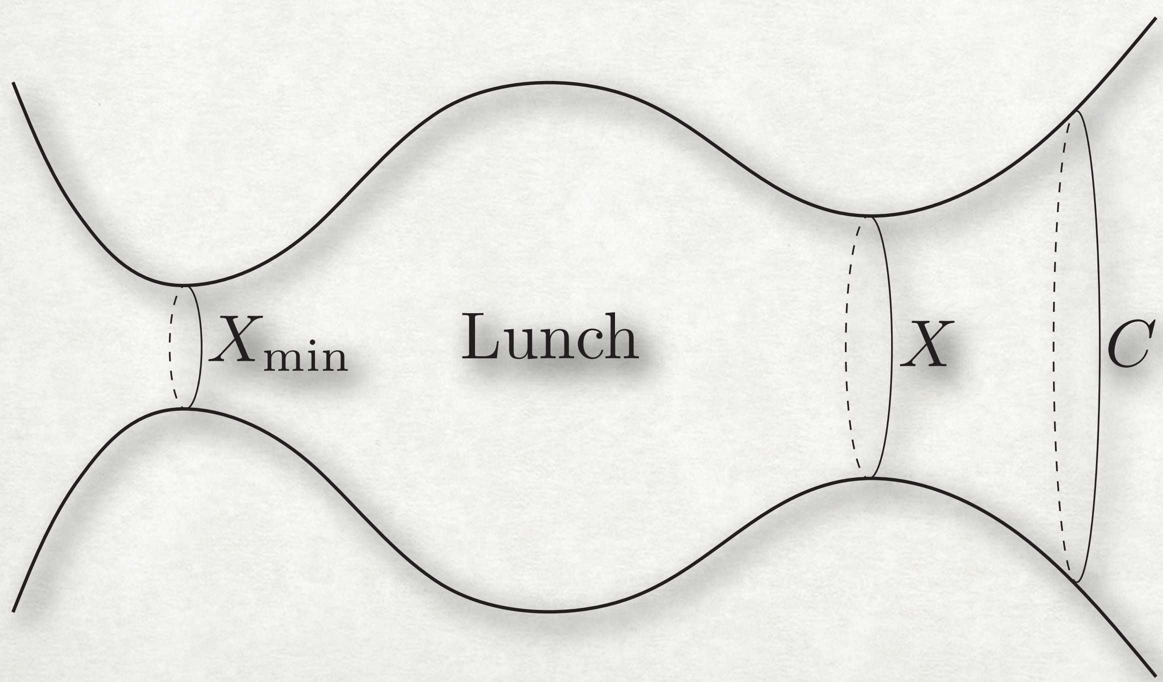
The geometric picture has done wonders for us on the Page curve. Can it help us with this?

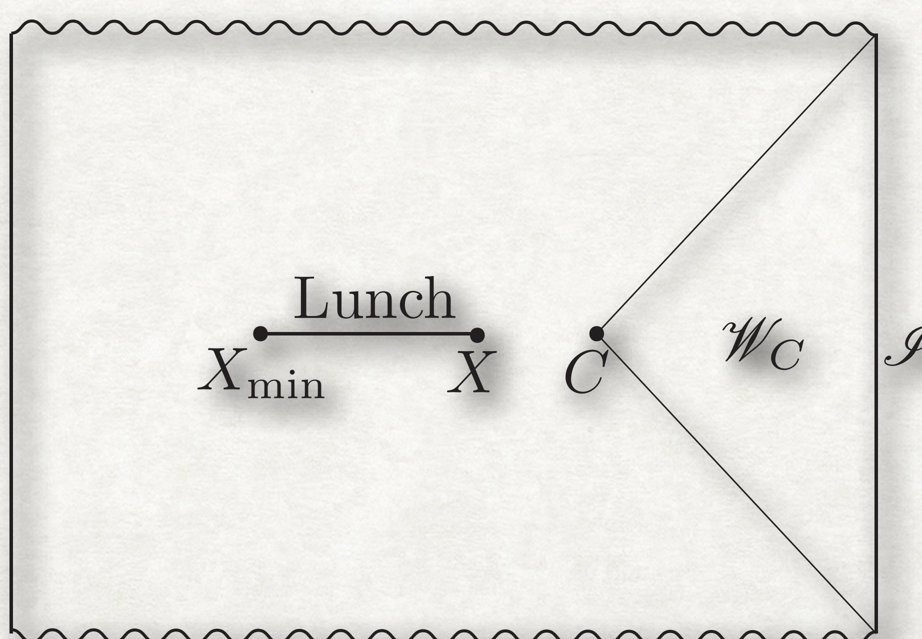
GEOMETRIZATION OF RECONSTRUCTION COMPLEXITY

THE PYTHON'S LUNCH

In the QES picture, the geometric avatars of exponential complexity are the non-minimal QESs: Brown, Gharibyan, Penington, Susskind





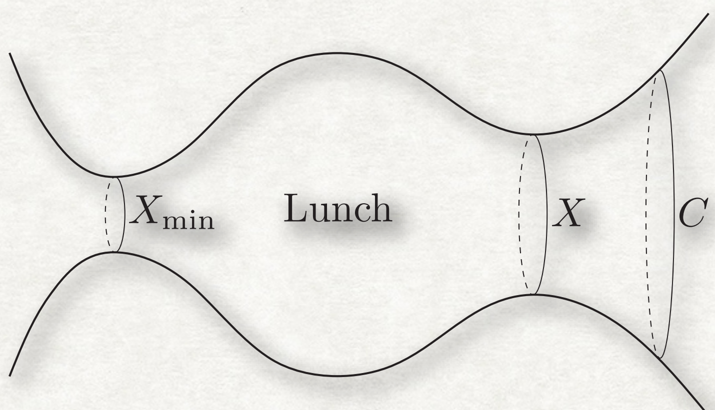


PYTHON'S LUNCH

Python's Lunch Proposal:

$$C \sim \text{Exp}\left[\frac{1}{2}\left(S_{\text{gen}}(\text{bulge}) - S_{\text{gen}}(X)\right)\right]$$

cf Geoff's talk: nonminimal QESs are the one and only source of exponential complexity in the AdS/CFT dictionary.

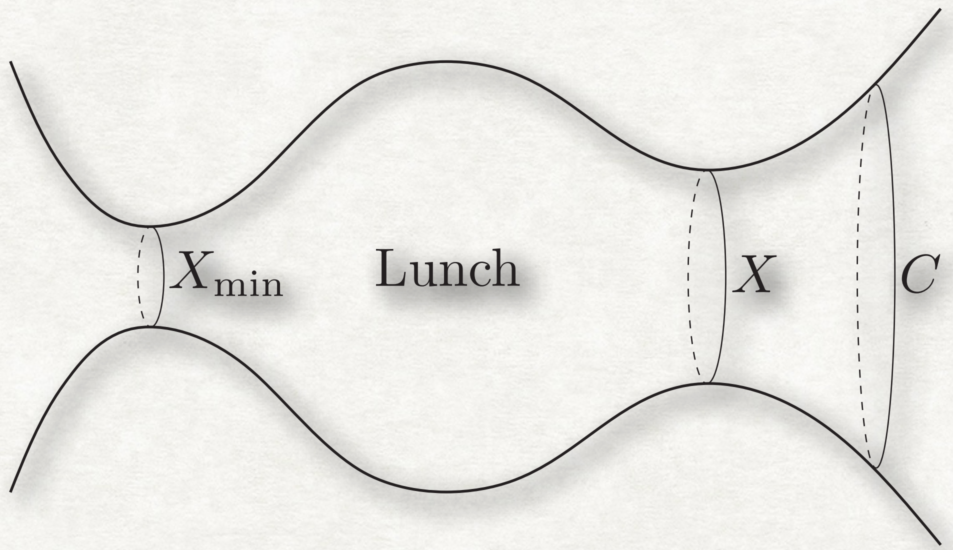


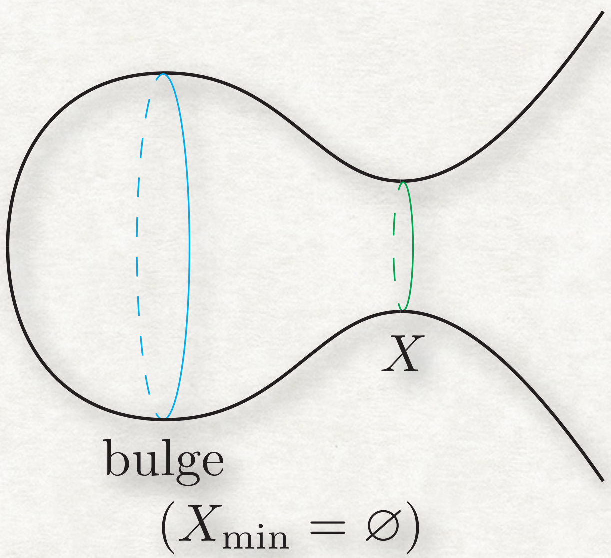
Consistency with gravitational path integral saddle calculations: if you use the "Hawking saddle", i.e. the wrong (subdominant) saddle — the nonminimal QES — then you don't know about the exponentially complex data and can't reconstruct the Hawking radiation.

CODE SUBSPACE AND RECONSTRUCTION

Whether a QES is minimal or not depends on the code subspace of bulk states under consideration for reconstruction.

When the code subspace is very large, less of the bulk admits a state-independent reconstruction Hayden-Penington; Akers-Leichenauer-Levine

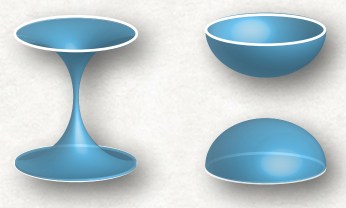




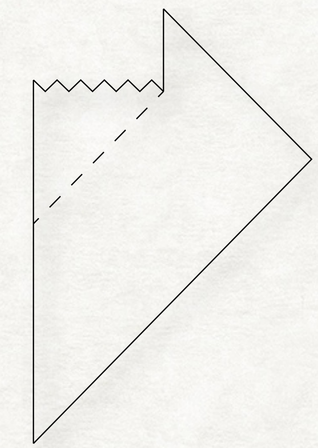
__Comment:__ What about **very** large code subspaces: typical state black holes? What about typical state arguments for **firewalls**?

QUESTIONS AND COMMENTS

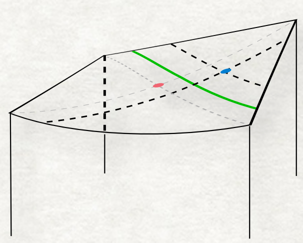
Why is semiclassical gravity - specifically the gravitational path integral - so smart?

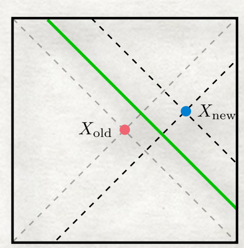


Beyond AdS?



What more can we learn from doubly holographic holography?

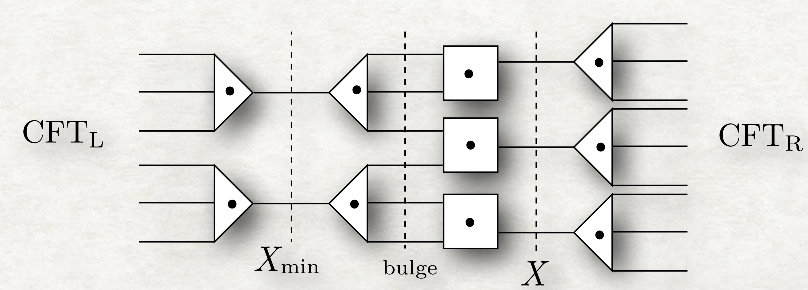




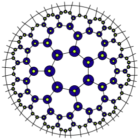
Soft modes?
Postselection?
Edge modes?

What about typical states?

What is the role of complexity in the resolution of the information paradox?



QES: Hilbert space perspective



1. We want to understand the QES formula!
2. It's derived from the Euclidean gravitational path integral, but that doesn't explain everything. E.g. computes $S_{BH} = A/4G$ but doesn't tell us the microstates we're counting.
3. We want a *Hilbert space* understanding of QES, microstates manifest.
4. One approach: understand as a consequence of $\mathcal{H}_{\text{bulk}}$ embedded into $\mathcal{H}_{\text{boundary}}$ like a quantum error-correcting code [Almheiri-Dong-Harlow].
5. Progress! Started in [Harlow] "Ryu-Takayanagi from QEC." Generalized to quantum minimal surfaces in [CA-Penington to appear].
6. Some lessons: Area is extra entanglement used to encode. Minimality from limited capacity for encoding.

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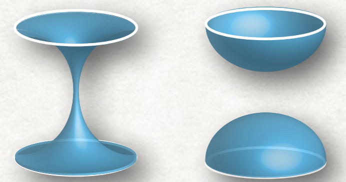

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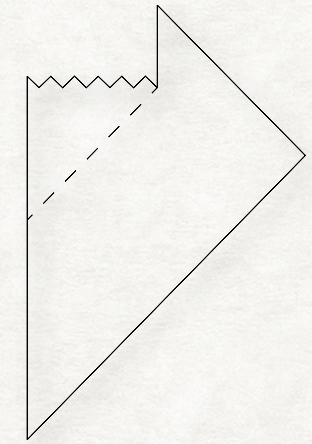

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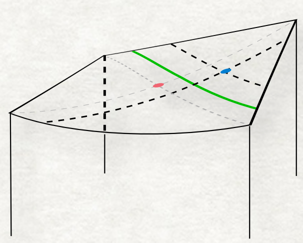

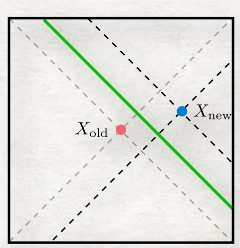

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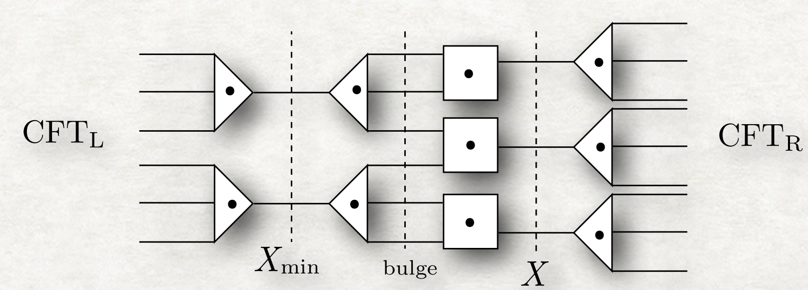
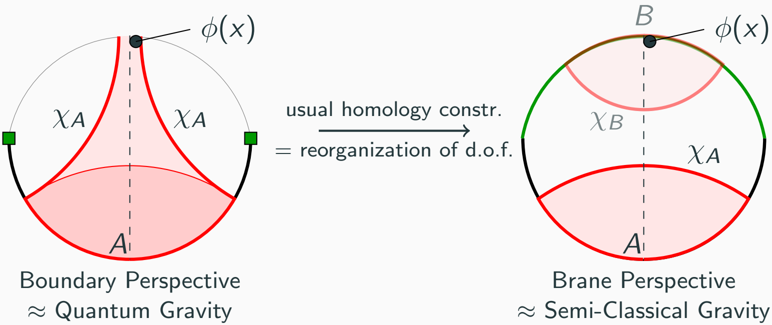


(More) Lessons from Double Holography

What role does semi-classical gravity play?

How to access the black hole interior in semi-classical gravity?



We still cannot access BH interior from semi-classical gravity.

Reorganization looks like coarse graining from the outside.

[arχiv:2105.01130]