Entanglement, Thermalization and Hawking-Page Transition in Quark-Gluon Plasma

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1 Introduction

High energy collisions posits a paradox. On one hand, experimental observations indicate thermal like properties in the final state of these collisions. These properties are best described when we assume the transient Quark-Gluon Plasma (QGP) to be in a fully thermal state. On the other hand according to the theory of Quantum Chromodynamics, these nuclear reactions, governed by Quantum mechanics, maintain unitarity of the S-Matrix. The former approach tells us that that QGP described by a fully thermal state, should have maximum entropy. However if we let unitarity do its job then the final state should conserve and not exhibit a high von Neumann entropy. In a pure quantum state of an isolated many particle system, the von Neumann entropy is zero[1] and thus under unitary time evolution entropy remains zero. Therefore, if we start with a pure state, the final state should have zero entropy. This apparent contradiction can be reconciled by considering QGP to be in a highly entangled state. This way the final state, that appears to be in a thermal ensemble, is considered to be in interaction with a heat bath. This tells us that the entropy associated with QGP shares insights with the black hole information paradox and therefore one should be able to reproduce the Page curve. Our aim thus is to be able to obtain a fundamental understanding of information theoretic properties of QGP in heavy-ion collisions in order to reproduce the Page curve using AdS/CFT correspondence[2]. We would further want to understand the apparent thermal state of QGP and be able to reconcile with the unitarity of the S-matrix.

Another obstacle in the path of a complete understanding, is the hadronization of QGP. Therefore we need to incorporate the confinement/deconfinement transition in our holographic models. One way to do this is by using some version of the Hawking-Page transition.

While heavy-ion collisions can generate conditions similar to the early universe, the time scales involved are vastly different. In the cosmos, we find that various particle species fall out of thermal equilibrium at different time scales due to cosmic expansion and cooling. This leads to different temperatures for cosmic

[1]This reflects the fact that a pure state has no uncertainty or lack of knowledge associated with it.

[2]It is important to note that the exact holographic dual for QCD is not known, one of the reasons being QCD is not conformally invariant. However holographic models with a QCD-like dual, that share important features with QCD, have been constructed and are quite successful in obtaining an equation of state

background radiation for different particles. However in our experimental setup, this different time scales for falling out of thermal equilibrium for different particles, is not observed[3]. This contradiction between what is observed in early universe and experiments can be explained by *Eigenstate Thermalisation Hypothesis*. The Eigenstate Thermalization Hypothesis (ETH) proposes that in certain quantum systems, individual energy eigenstates can exhibit statistical properties similar to those of a thermal ensemble. This means that even though the system may not be in thermal equilibrium, by considering the properties of individual energy eigenstates and appropriately weighting them, the statistical behavior of the system resembles that of a system in thermal equilibrium.

The aim of this review is to extensively use the ideas of dualities in physics and use concepts from black hole physics, statistical mechanics and quantum gravity to obtain a fundamental understanding of the theory of fundamental particles; quarks and gluons, and instil a sense of excitement in both the reader and author of this article.

2 Entanglement Entropy

In high energy heavy-ion collisions it is often difficult to measure the complete final state due to a number of factors like, multiplicity of particles, detector coverage, background noise etc. Therefore one instead measures a subset of all emitted particles within a certain rapidity which is much smaller than the full range $\Delta y \sim 1$. Let the full final state be Φ, then the subsystem within the rapidity is $\Phi_{\Delta y}$ and the rest of the system outside this rapidity window is given by,

$$\Phi_{\Delta y'} = \Phi / \Phi_{\Delta y}.$$

The state $\Phi_{\Delta y}$ is entangled with $\Phi_{\Delta y'}$ and therefore carries an entanglement entropy which is given by,

$$S(\Phi_{\Delta y}) = \mathrm{Tr}[\rho(\Phi_{\Delta y}) \ln \rho(\Phi_{\Delta y})],$$

[3]Consider for example the case of Pb-Pb collisions

where $\rho(\Phi_{\Delta y)}$ is the reduced density matrix of the subsystem in consideration and is calculated by tracing out the system outside the rapidity window,

$$\rho(\Phi_{\Delta y}) = \mathrm{Tr}_{\Phi}[\rho(\Phi)].$$

In QCD we know that the S-matrix is unitary, which means if the initial state is a pure state then $S(\Phi) = 0$. For the rapidity window Δy much smaller than the full range, $S(\Phi_{\Delta y})$ grows with the size of the rapidity window. In other words, as the size of the rapidity window increases, the entanglement entropy between particles within that window also increases. At high collision energies, there's a phenomenon known as boost invariance, particularly at midrapidity. From boost invariance, for small windows of rapidity, $S(\Phi_{\Delta y})/\Delta y$ remains almost constant. Now the *complementarity law of quantum mechanics*, which says that the entanglement entropy of a system is equivalent to the entanglement entropy of its complement, suggests,

$$S(\Phi_{\Delta y}) = S(\Phi_{\Delta y'}).$$

Now, when the rapidity window expands, beyond half the total rapidity range, the entanglement entropy begins to decrease[4]. Eventually, when the rapidity window approaches twice the beam rapidity , the entanglement entropy approaches zero. Thus entanglement entropy associated with a rapidity window reproduces the Page curve. See [**Figure 1**].

Page Curve for Black holes

The Page curve was initially introduced to resolve the black hole information paradox[**11**]. However it is widely used as a characteristic property of any generic quantum many-body system. Let us try to understand the original argument.

When the black hole is formed due to the gravitational collapse, the entropy (before the onset of hawking radiation) is zero. As the black hole begins to emit radiation, the radiation that comes out is entangled with the one that goes in. Near the black hole's event horizon, due to quantum fluctuations, virtual

[4]Think of it this way, the broader the rapidity window, more the particles with varying degrees of correlation and entanglement. Hence the correlation decreases.

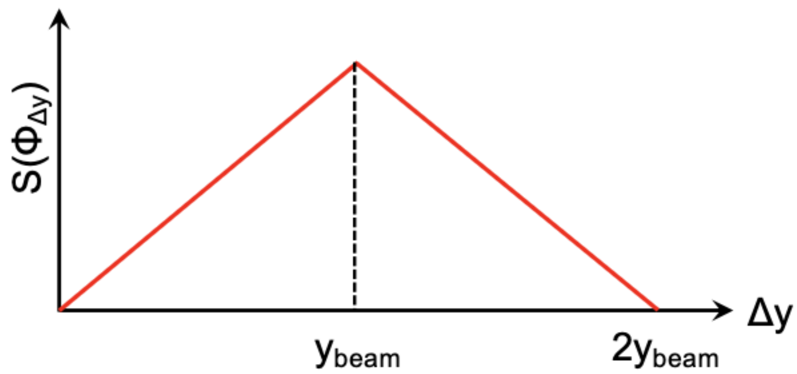

Figure 1: Page cure for the entanglement entropy associated with a rapidity window [**1**]

particles come into existence for a short period of time before they are annihilated by each other. Virtual particles are a pair of negative and positive energy excitations and in the short period of their existence, if the particle with negative energy happens to fall into the Black hole, the annihilation doesn't occur and instead the particle with positive energy seems to come out of the black hole as *Hawking Radiation*[5]. If we just look at the outgoing radiation, we find that it has some non zero entanglement entropy. Thus from the onset of hawking radiation till half of the black hole is evaporated the entanglement entropy increases. Let Alice be outside the black hole and is receiving Hawking radiation. Due to entanglement she will only have 'some' of the information with her while 'some' is goes into the black hole[6]. After half of the black hole is evaporated, the entropy begins to decrease and reaches zero when the black hole is completely evaporated. The time it takes for half of the black hole to evaporate is called *Page time* and the curve that entropy traces with time is the *Page curve*. See Figure [**Figure 2**] The shared paradox of black hole information and the apparent thermal state of QGP tells us that that reproduction of Page curve is extremely crucial.

3 Eigenstate Thermalisation Hypothesis

In many-body quantum systems with chaotic dynamics, the behavior of individual eigenstates becomes highly intricate. Despite each eigenstate representing a specific energy configuration of the system, chaotic interactions between particles lead to a phenomenon called quantum chaos. Quantum chaos implies that the

[5]This way due to the negative energy particle falling into the black hole, the black hole loses its mass.
[6]Consider a bell pair. Where one qubit goes in and one comes out.

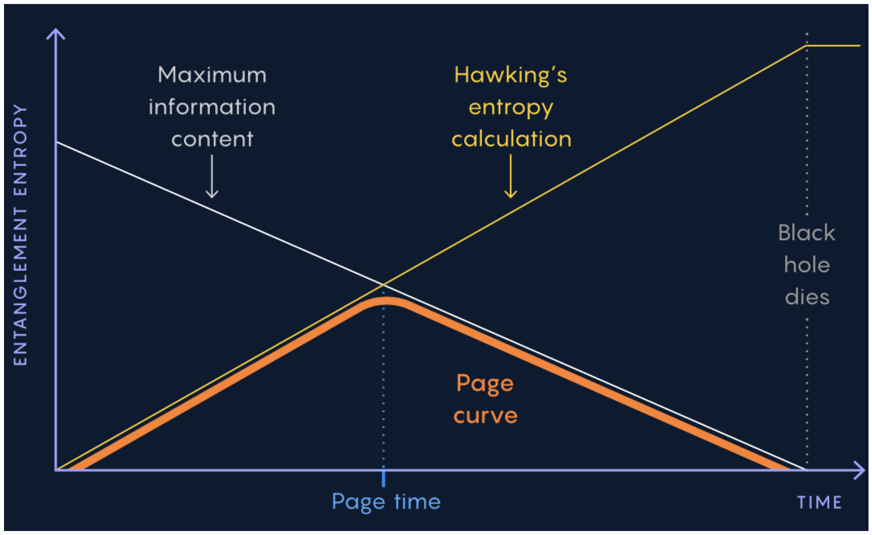

Figure 2: Amount of Hawking's entropy of a black hole and its entanglement entropy.[7]

system explores a vast and intricate configuration space. Therefore, in a many-body quantum system, the states are highly entangled with each other and as a result, the observables of a single particle are influenced by the entire system's dynamics. Eigenstate Thermalisation Hypothesis posits that these entanglements effectively 'spread out' the influence of the system's energy across all its degrees of freedom, and this leads to emergence of a thermal-like behavior in individual eigenstates. Consider an observable A, according to the Random Matrix Theory, the matrix elements of these observables in the energy eigen basis,

$$A_{\alpha\beta} = \langle E_\alpha | A | E_\beta \rangle .$$

The ETH says,

$$A_{\alpha\beta} = A(E)\delta_{\alpha\beta} + e^{-S(E)/2} f(E,\omega) R_{\alpha\beta},$$

where $E = E_\alpha + E_\beta/2$ and $\omega = E_\alpha - E_\beta$. The off diagonal elements, describing the transition between different eigenstates of the system, can be written as normalised elements of the random matrix modified $S(E)$ and $f(E,\omega)$. $S(E)$ is the microcanonical entropy that characterises the number of accessible states of the system at a given energy E. It quantifies the system's disorder of multiplicity of states within a narrow energy range. $f(E,\omega)$ is the spectral function that describes the density of states of the system as a function of E and frequency ω. It provides information about the distribution of energy levels and transitions between them. Notice that the individual off-diagonal elements are suppressed for a system with a high energy level density. Therefore we only need the diagonal matrix elements to determine the thermal average of the observable,

$$\langle A\rangle_T = Z(T)^{-1}\int \frac{dE}{E} e^{S(E)-E/T} A(E)$$

$$Z(T) = \int \frac{dE}{E} e^{S(E)-E/T}.$$

If we assume ETH, it is possible to show that the system prepared in an energy eigenstate behaves like a thermal system. Further ETH gives us insights on the following properties;

- **Long-Time Average Equals Thermal Average (A** $= \langle A\rangle_T$**)**:
  - When a quantum system is prepared in an energy eigenstate, the long-term average of any observable quantity A is equal to the thermal average of that observable. In other words, if you repeatedly measure the value of A in a system prepared in a some energy eigenstate and then average those measurements over a long period, you'll obtain a value similar to what you would get from a thermal ensemble at that temperature.
- **Quantum Fluctuations Match Thermal Fluctuations (with Corrections of** $O(1/N)$**)**:
  - The quantum fluctuations observed in the system, prepared in an energy eigenstate, align with those expected from thermal fluctuations, with corrections of the order $1/N$, with N being the number of degrees of freedom in the system.
- **Kubo Relation for Time Correlation Functions with Spectral Density** $f(E,\omega)$:
  - The Kubo relation is a fundamental result in statistical mechanics that relates the time correlation function of an observable to the spectral density of the system. According to ETH, the time correlation function of finite-time expectation values $\langle A\rangle_t$ obeys this Kubo relation, with the spectral density $f(E,\omega)$. Due to this we get insights on the dynamical behavior of observables of the system from its underlying spectral properties and further tells us how the system evolves over time.

Another important factor is the *Thouless energy* which is defined as the energy difference ω, below which the factor $f(E, \omega)$ in the ETH can be replaced with a constant for most observables. When ω is smaller than E_{Th}, the system's behavior approaches the Random Matrix Theory (RMT) limit, where the spectral correlations of the system are described by random matrix theory. In a dynamically evolving quantum system, the energy differences ω is inversely related to the evolution time. This means that shorter evolution times correspond to larger energy differences ω, while longer evolution times correspond to smaller ω. The Thouless time (t_{Th}), defined as $\hbar/E_{\mathrm{Th}}$, represents the time scale associated with the Thouless energy. In numerical studies of discrete quantum systems, it has been found that the time until full ETH behavior is established, t_{ETH}, can be much longer than the Thouless time t_{Th}. It represents the time it takes for the system's observables to converge to the thermal-like behavior predicted by the ETH.

Importantly, t_{ETH} can be much longer than t_{Th} by a factor that scales with the size of the system. This implies that the establishment of full ETH behavior may require significantly longer evolution times, particularly for larger systems.

The establishment of quantum entanglement requires causal connections across the entire system. This process takes time, and full entanglement is only reached asymptotically as the system evolves. According to the ETH, once a system becomes fully entangled, its observables behave as if the system is in contact with a heat bath, even if only a small part of the density operator contributes to the observable. In other words, if the trace is taken over more than half of the states of the system, the behavior of the observable resembles that of a system in thermal equilibrium. In the context of heavy-ion collisions, one can attribute ETH to explain the success of the thermal model. The onset of ETH behavior depends on the specific operator being studied. This variability may help us understand why the actual number of hypertritons observed in p+Pb collisions differs from what the thermal model predicts. The interesting question is whether the time it takes for hadronization to occur (t_{H}) is longer or shorter than the time it takes for ETH behavior to establish (t_{ETH}). Hypertritons have larger wave functions compared to protons, which suggests that their formation involves a stronger suppression of matrix elements, leading to a longer t_{ETH}. On the other hand, the proton-sized fireball produced in p+Pb collisions implies a shorter t_{H}. This tells

time	HIC phenomenology	Holographic dual model
Stage I $t \leq 1$ fm/c	**Hydrodynamization** hydrodynamic attractors lead from transient large amplitude fluctuations to viscous hydrodynamic expansion	**Numerical AdS simulations** entropy production mapped by apparent horizon $t \leq 0.2$ fm/c equilibration without fluctuations $t \leq 1-2$ fm/c equilibration with fluctuations
Stage II $t \leq O(15)$ fm/c	**Expansion of the QGP fireball** hadronization at QGP surface	**Collision of localized shocks** [62] (Sections V and VII)
Stage III $t \approx O(15)$ fm/c	**Bulk hadronization** chemical freeze-out	Smoothed **HP transition** (Sections VII and IX)
Stage IV $t \geq O(15)$ fm/c	**Expansion of HRG** kinetic freeze-out	**Entangled hadrons** network of ER bridges (Section VIII)

Table 1: The different stages of a heavy ion collision (HIC) and their proposed holographic modelling [**1**].

us that ETH behavior may not have fully set in when hypertritons are formed in these collisions, which could further explain why their observed yield is lower than predicted by the thermal model.

As explained above, ETH applies to systems exhibiting quantum chaos, However, its validity for QCD remains a conjecture. Since classical non-abelian gauge theories, like QCD, exhibit chaotic behavior, in principle, one can attempt to confirm ETH for highly excited energy eigenstates in QCD. The validity of ETH for QCD is an interesting field of study that may lead us to a much better understanding of fundamental particles.

4 Time Scales in the collisions

In heavy ion collisions, the process of thermalization involves several distinct time scales. Initially, the system is far from thermal equilibrium however, due to rapid longitudinal expansion, it has limited time to reach equilibrium. Within this short time-frame, the quark-gluon system undergoes hadronization, which significantly alters its properties. The various stages are giving in the [**Table 1**]. This transition is viewed as an early stage of "chemical freeze-out," which later moves on to a complete kinematic freeze-out. Since the colliding nuclei has a very large momenta, this means there will be large Lorentz factors. Therefore, transverse extent of the colliding nuclei at the initial collision is much larger than their longitudinal thickness. Due to these various time scales, it becomes extremely difficult to build a holographic model that perfectly spans the entire collision. However all the time and length scales observed in heavy ion collisions can be attributed to three primary scales associated with the underlying field theory and the initial and spatial boundary conditions:

1. The initial energy density ε_0 deposited in the collision.
2. The initial size of the collision area
3. The confinement scale of QCD Λ_{QCD}.

These factors also have equivalents in the AdS/CFT dual description.

1. The initial energy density ε_0 of the shockwave collision.
2. The initial size of the collision area.
3. In holographic models, an additional length scale that marks the transition, knowin as the Hawking-Page transition, between confined and deconfined phases.

Hawking-Page Transition

The Hawking-Page transition refers to a phase transition in AdS spacetime. As the temperature of the system decreases, there is a critical temperature below which the system undergoes a phase transition from a thermal gas of gravitons to a stable black hole. In the context of heavy ion collisions, we argue that the Hawking-Page transition may play a role in understanding the transition from a confined state, to a deconfined state[7].

When the dual representation is restricted to the Poincaré patch of AdS space, essential for depicting

[7] We will learn more about this in the next section

heavy ion collisions, the introduction of a third scale becomes imperative. Thus we need to make adjustments in our holographic dual in order to incorporate this scale. Which will break the the conformal invariance, in order to accurately portray the process of hadronization.

While the holographic model may not precisely replicate an actual heavy ion collision, it holds the potential to offer valuable conceptual insights. Consider the final state where the entire system comprises of hadrons moving freely towards the detectors. In this case, there are two potential outcomes: either the hadrons exist in thermal equilibrium, described by a high-entropy density matrix, as commonly assumed in heavy ion physics, or they form a highly entangled, nearly pure quantum state with minimal entropy. We will see later that the second case, the holographic dual of an entangled state of many hadrons, differs only in subtle ways from the first case, holographic dual of a QGP fireball. Implying that, a holographic description can extend smoothly beyond the hadronization transition.

Another crucial question revolves around determining whether the fireball attains ETH-like behavior prior to hadronization. It's important to find out how long it takes for few-particle observables, suitable for experimental measurement, to closely approximate their thermal values. The time necessary for entanglement to spread throughout the fireball sets a minimum threshold.

In this review we want to potentially extend the effective holographic model of heavy ion collisions beyond the Page time. A key aspect is preserving complete quantum coherence. We will need to expand numerical simulations of AdS gravity to encompass the global AdS geometry, not just the Poincaré patch.

The underlying notion is that a heavy ion collision goes from a highly entangled wave functions of the colliding nuclei to a higly entangled QGP. Which further evolves into a multi-hadron state without ever reaching a genuinely thermal state with significant von Neumann entropy. We can think the collision as a unitary S-matrix, which maps the initial state to the final hadron states. Thus, the apparent thermal behavior of certain local observables in intermediate states becomes insignificant. The thermal entropy arises from the interaction of emitted hadrons with detectors.

The feasibility of detecting complex entanglement features among emitted hadrons in heavy ion collisions remains uncertain, much like the practicality of testing the entanglement pattern of Hawking radiation from an isolated evaporating black hole. However, experiments with atomic physics analogues of black holes do offer hope for investigating such phenomena.

Since QED and QCD share information-theoretical properties due to time reversal invariance, experimental confirmation of ETH behavior and Hawking radiation in QED systems suggests similar behavior in QCD systems. However, the practical applicability of these insights depends on whether a holographic description of entanglement and ETH behavior can be accurately realized.

5 Hadronnization as an AdS Phase Transition

The Einstein equations with a negative cosmological constant offer two solutions featuring asymptotic AdS geometry: plain AdS space and a black hole within AdS space. The black hole geometry, characterized by the Schwarzschild horizon, is mapped to deconfinment in the dual gauge theory. At low T values, plain AdS space exhibits the lowest Euclidean action. Beyond a certain temperature T_c, determined by the specifics of the dual gravity theory, the AdS-BH geometry emerges with the lowest free energy. This is called the "Hawking-Page" transition. In the simplest holographic model, of $(d+1)$-dimensional Einstein action with negative cosmological constant $\Lambda = -\frac{d}{L^2}$ on global AdS space, the transition is abrupt and one may call it a first-order phase transition. In the dual gauge theory, the Hawking-Page transition corresponds to the confinement-deconfinement transition.

In the conformal, large-N_c super-Yang-Mills theory, the Hawking-Page transition refers to a first-order phase transition. A similar behavior is seen in the non-supersymmetric $SU(N_c)$ gauge theory, particularly for $N_c \geq 3$. To model these gauge theories more accurately, gravity dual models are constructed by introducing a dilaton field to five-dimensional Einstein gravity, representing the gauge coupling constant. These gravity duals exhibit a first-order deconfinement phase transition, just like the conformal Super-Yang-Mills theory.

In contrast, the deconfinement transition in Quantum Chromodynamics is known to be a smooth crossover.

Dual dilaton gravity models have been studied to understand the thermal properties of QCD, incorporating fundamental matter like quarks to mimic its running coupling and chiral properties. Some models do have the flexibility to transition from a first-order phase transition to a crossover transition.

The dynamics of the bulk transition depend heavily on the rate of temperature decrease. A slow cooling rate leads to a transition near the critical temperature T_c through a mixed phase characterized by bubble formation. Conversely, rapid cooling triggers a transition via a Gregory-Laflamme[**8**, **9**] instability from a supercooled phase at $T_{\min}$. While the latter scenario is predominant in the limit of large N_c, it is likely that for holographic models of QCD with $N_c = 3$, the former scenario is realized, particularly in heavy ion collisions. Smooth crossovers typically exhibit the first scenario.

6 Hadron Emission = Hawking Radiation

Black hole information paradox and the apparent thermal QGP paradox are two sides of the same coin. Thus we can, leverage insights from the black hole community, to construct a model that treats hadronization analogous to Hawking radiation. In this analogy, the hadrons can be thought of as the Hawking radiation outside the black hole horizon, since hadrons cannot exist within the Quark-Gluon Plasma. One can think of the surface as a horizon for them. Photon pair creation at the black hole horizon is paralleled by hadronic particle-hole production at the QGP surface, where the ingoing hole state is absorbed. The entanglement between the outgoing hadron and the interior of the shrinking QGP fireball, is similar to island formation in black hole decay. The core idea driving this analogy is that black hole decay results in a Page curve for the entropy of Hawking radiation outside the horizon, which is also anticipated for the hadronic state outside the QGP. Complete entanglement among the hadrons is only attained at the culmination of hadronization. This analogy essentially explains the apparent thermal behaviour of QGP. This characteristic is not readily comprehensible without entanglement, as different hadrons scatter differently and are thus expected to decouple from the expanding fireball at different times. This alignment could be naturally accounted for if a highly entangled QGP state and a highly entangled hadronic state are fundamentally indistinguishable.

A short note on Islands

Similar to the Feynaman path integral where we sum over all the possible paths that a particle can take, Gravitational path integral sums over all the possible geometries that a black hole can go through. Using the Gravitational path integral we find a formula for the von Neumann entropy of a black hole, which is similar to the Bekenstein-Hawking entropy. The only difference is the choice of the dividing surface. We choose a surface such that the total entropy of a black hole is minimized. This minimal value is the fine-grained entropy. When we find the fine-grained entropy of an evaporating black hole the Gravitational path integral sums over all kinds of geometries that the black hole goes through as it radiates out hawking radiation. One of these geometries, is the one where the black hole is connected to replicas of the same black hole. These black holes are connected via wormholes, also called the Einstein-Rosen (ER) bridge. The entropy of one black hole is calculated by calculating the entropy of n black holes and then taking $n \to 1$[8]. Note that these wormholes don't really exist but just like Feynman Path Integrals, where we sum over all paths even those with negligible probability, the possibility of the wormhole geometry existing, alters the entropy of the black hole. The information that is in the outgoing radiation is entangled with the information in the interior of the black hole. Thus in order to find the fine-grained entropy, we want to minimize the '*total*' entropy, and thus we would have to add the entropy of the inside region as well. This fine-grained entropy accurately follows the *Page curve*. Therefore the generalised entropy of the radiation is the combined entropy of two regions. The region of radiation itself and the region inside of the black holes called *Islands*[**10**]. According to this idea, information that falls into a black hole is not lost but instead gets encoded in subtle correlations between the interior and exterior of the black hole.

7 Holographic Description of Hadronization

The initial state in a heavy-ion collision, is highly entangled, characterized by a density matrix describing the approaching nuclei. This entangled state evolves into another highly entangled state before being

[8]This is also called Renyi Entropy

projected onto hadron states. However, this projection leads to decoherence and entropy production due to the interaction with the detector. For a realistic holographic description of such collisions, it's crucial to account for entanglement at each stage. While numerical solutions of classical Einstein equations fall short in this regard, we argue that an approximately valid AdS model capable of tracking entanglement during transitions like the Hawking-Page type should exist. This argument is supported by the monogamy of entanglement principle, which implies that the effects of entanglement are negligible for observables involving only a few hadrons.

We propose a scenario that combines the presence of two hadronization mechanisms: individual hadron emission from the QGP fireball surface and instantaneous hadronization of the remaining fireball at the critical temperature (T_c). The QGP fireball's transverse size remains relatively constant over time due to a balance between internal cooling from hydrodynamic expansion and evaporation from its surface. Throughout this period, the surface temperature of the QGP fireball remains fixed at (T_c), while the volume of the hadron resonance gas (HRG) outside the fireball continuously increases. Once the QGP fireball's temperature reaches (T_c) uniformly, the remaining volume rapidly undergoes hadronization. In the context of the AdS dual description, the spatially bounded region corresponding to the QGP fireball on the AdS edge extends into the AdS bulk until it encounters a spatially bounded black hole (BH) horizon. It is conceivable that this region in AdS space should be modeled as the holographic dual of a boundary conformal field theory (BCFT). The emitted hadrons become entangled with states on the BH horizon via Einstein-Rosen (ER) bridges, resulting in no entropy production. See [**Figure 3**].

As discussed before, the process of hadronization is described by the "chemical freeze-out." which aims to explain the thermal behaviour, despite ongoing hadronic interactions within the expanding hadron gas.

However, we argue the success of the thermal model can be attributed to quantum coherence, in the form of ETH. According to this perspective, the system's thermal behavior emerges naturally from the coherent evolution of its quantum states, obliterating the need for a chemical freeze-out.

Currently we do not have a reliable quantitative description of these intermediate stages, where we can explain entanglement at each stage, neither in QCD nor in holography. Therefore, we need a holographic

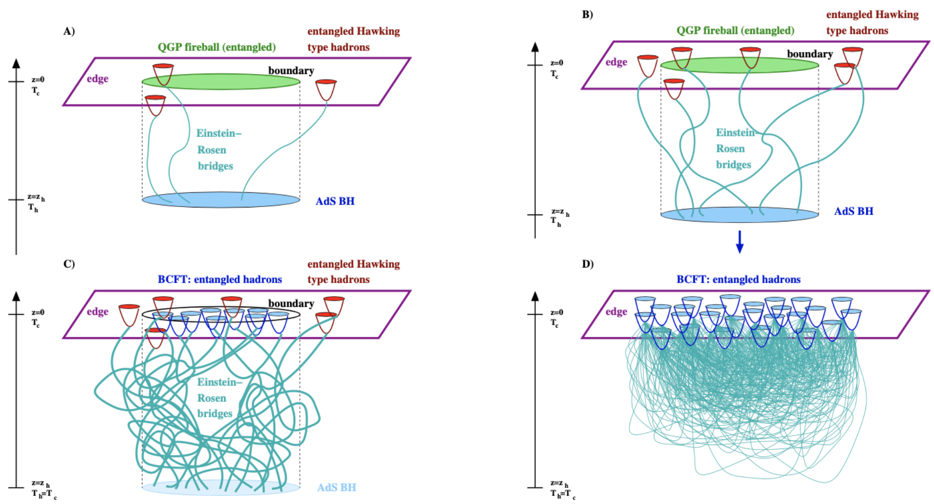

Figure 3: Different stages of a high energy heavy ion collision. A) After the QCD fireball is formed hadrons are emitted from its surface in analogy to Hawking radiation. B) This leads to volume growth of the whole QCD system on the edge. In parallel the fireball cools, e.g. the dual black hole sinks deeper into the AdS throat. However, the 3-dimensional volume of the QGP fireball and thus the 3-dimensional volume of the AdS BH remains roughly constant. C) When the temperature of the fireball, which is identical to that of the AdS black hole, reaches T_c the Hawking-Page-like transition occurs corresponding to complete hadronization of the remaining fireball on the AdS edge. D) Due to the monogamy of entanglement any pair of hadrons in the state after the hadronization transition can only share a very small fraction of entanglement, on average proportional to $O(1/N_h)$ with N_h being the number of hadrons.[**1**]

model where mapping a purely hadronic late stage should be a smooth crossover rather than a first order phase transition.

8 Conclusions: What next?

The discovery of dualities in physics has been revolutionary. One of the most crucial goals of physics is to understand the fundamental nature of the universe and dualities has made this goal a lot more achievable than before. These dualities allow us to map one field onto an entirely different one, facilitating the understanding of complex phenomena using well-established models. AdS/CFT, in particular, has greatly enhanced our comprehension of QCD thus far and holds promise for future investigations. The ideas discussed in this review open avenues for exploring and potentially answering several key questions:

- Does QCD exhibit behavior consistent with the Eigenstate Thermalization Hypothesis (ETH)?
- Is ETH a necessary condition or merely sufficient to account for the success of the thermal model? If it is indeed necessary, how long does it take for few-particle observables to approximate thermal behavior?
- Have recent advancements in numerical solutions of gravity in AdS space improved our understanding of the dynamics involved in a Hawking-Page type transition?
- Could holographic models, in which the transition resembles a smooth crossover akin to QCD, offer an approximate link between the Hawking-Page transition and the hadronization of a quark-gluon plasma?
- Can the emission of hadrons from the surface of a quark-gluon plasma be effectively modeled as splitting quenches?
- How can we validate the analogy proposed between hadronization and black hole decay?

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