Title: Reflections on the black hole information problem

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Reflections on the black hole information problem

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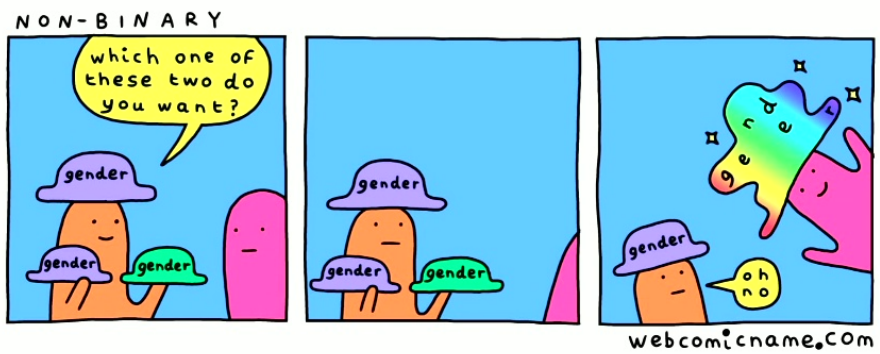
Emmy Noether workshop on Quantum SpaceTime

$\vec{x} =$ Perimeter Institute

$t =$ 2025-03-13 @ 11:15



[1] My contact details aren't on my department's website because of harassment. Open invitation: please ask me in-person for my email and/or phone number.

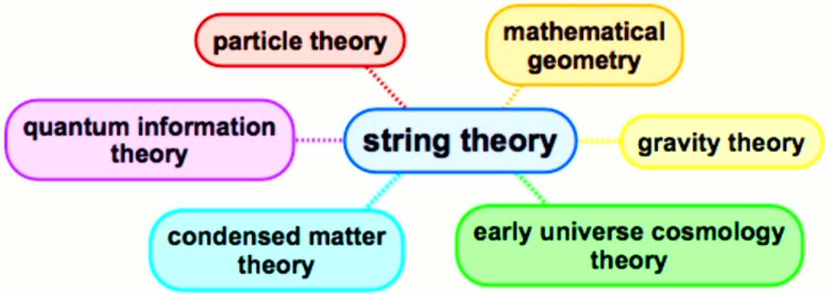
Positionality

- My cultural reference frame: New Zealand.

- This is the first research meeting I have participated in since brain and other neurological symptoms of Long Covid began in late 2022. Please be kind?
- All of the various approaches to Quantum SpaceTime, the topic of this beautifully designed workshop, are interesting and valuable. I hope we are all keener now on cooperation between our various approaches – I know I am!
- Advice for all ages: over $> 1/3$ century, I learned the hard way to respect **Shenker's theorem**: whatever you think is the *most missable* aspect of theoretical physics today will be *exactly* what you need to learn tomorrow.
- As a tenured full professor in STEM, I want to be clear that I also value other academic fields, including social sciences, humanities, arts, as well as knowledges held by other longstanding communities outside of academia.

Toolbox choices

- What I like the most about string theory (+ holography, which grew out of it) is its highly nontrivial cross-fertilization with a wide range of adjacent fields. Fruitful conversations from my own research history include:-



- What I like a lot less about string theory – and more broadly theoretical high-energy/subatomic physics – is that other physicists often perceive us as arrogant, as individuals and as a group. So as a community we definitely have a bunch of homework to do, in relation to making the atmosphere more welcoming to gender minorities of all kinds including cisgender women.
- Goal today: our two toolboxes may have more to offer than you appreciate.

Black holes as a theoretical laboratory

- Hawking'74: Sorry, y'all – classical black holes appear to eat quantum field theoretic information. Even my radiation isn't enough to retrieve it all.
- Breakthrough Prize 2017: A. Strominger + C. Vafa, J. Polchinski.
  - S_{BH} can be computed from statistical mechanics of strings and branes.
  - How far outside the horizon does low-energy effective field theory fail?
- New Horizons Prize 2015: H. Casini + M. Huerta, S. Ryu + T. Takayanagi.
  - Entanglement entropy in QFT is super important.
  - In the context of AdS/CFT holography, EE can be geometrized.
- New Horizons Prize 2018: D. Stanford
  - Quantum chaos plays a crucial role in gravity, for BH in particular.
- New Horizons Prize 2019: D. Harlow, D. Jafferis, A. Wall.
  - On the nexus between quantum information and quantum gravity.
- New Horizons Prize 2021: A. Almheiri, N. Engelhardt, H. Maxfield, G. Penington.
  - On the quantum information content of a black hole and its radiation.
- Many others also contributed to this field. Without subtracting from above brilliances one bit: this list of laureates is overly male, white, and American.

Holographies

- The OG AdS/CFT correspondence was discovered in the context of string theory (D-branes, etc.). Later on, it was realized that holography does not actually require string theory. So you can be a holographer while being agnostic on whether string theory is *the* theory of quantum gravity.
- Holographic conformal field theories (CFTs) are a small subset of all CFTs. They should satisfy two physically important conditions:-
  1. a large number N of field degrees of freedom;
  2. a sparse spectrum of operators with low conformal dimension.

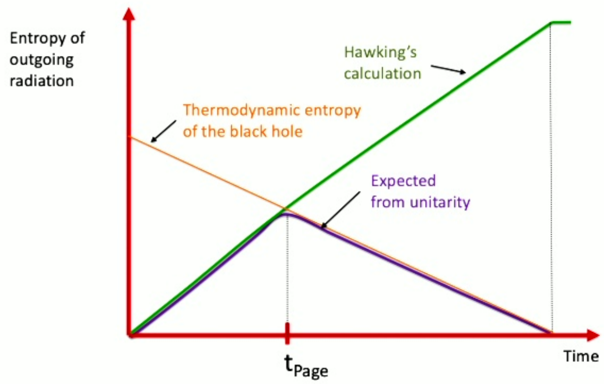
  This ensures the bulk dual is Einstein gravity plus small $[g_s, \alpha']$ corrections.
- AdS/CFT is a strong/weak coupling duality, which makes it powerful. And a black hole in AdS corresponds to the CFT at the Hawking temperature.
- More recently: pile of evidence for flat holography. dS/CFT is harder; a WIP.
- AdS_{D+1}/CFT_D in $D \geq 1+1$ matches a specific bulk theory to a specific CFT. The case of nearly AdS_2/nearly CFT_1 is qualitatively different. It matches a 2D bulk gravity theory with a 1D random matrix model: JT/SYK = Jackiw-Teitelboim/Sachdev-Ye-Kitaev. 1D SYK couplings sampled from different *ensembles* correspond to different details of the 2D bulk theory.

Entanglement and the Page curve

- Consider entanglement entropy S_{ent} between quantum field theoretic degrees of freedom in region $\mathcal{R}$ on boundary of AdS and those in its complement region $\bar{\mathcal{R}}$. Ryu-Takayanagi'06: S_{ent} is geometrized as area of minimal bulk extremal surface that ends on $\mathcal{R}$

$$S_{ent} = min_{\chi} \{ext_{\chi} [A(\chi)/4G_N]\} .$$

- Suppose a BH forms from collapse of a pure state. S_{BH} must $\downarrow$ with time, because $A \downarrow$ as H.rad $\uparrow$. By contrast, $S_{rad} \uparrow$ with time, as each new Hawking pair is created fresh from vacuum near the horizon. Are these facts consistent?
- In a unitary theory of quantum gravity, S_{rad} should really follow the Page curve, which $\uparrow$ until it reaches S_{BH}, and then any further emitted radiation should start to purify previously collected radiation, bringing S_{rad} back down to zero again.



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Islands and wormholes

- Penington'19, Almheiri-Engelhardt-Marolf-Maxfield'19: gave prescription reproducing the Page curve. End of BHIP announced [again].

$$S_{gen} = \min_{\chi} \{ext_{\chi} [A(\chi)/4G_N + S_{sc}(\Sigma_{rad} \cup \Sigma_{island})]\} \ ,$$

  where χ = minimal quantum extremal surface,
  S_{sc} = semiclassical entropy of matter fields on union of
  Σ_{rad} = exterior portion of Cauchy slice where radiation is collected +
  Σ_{island} = new portion of Cauchy slice lying inside black hole horizon.
- The generalized entropy formula with the Island was found by using the replica trick formalism, and including the effects of replica wormholes, in the context of the gravitational path integral (GPI).
- Guo-Hughes-Mathur-Mehta'21: the wormhole paradigm appears to require some kind of nonlocality linking the hole to its distant radiation?
- So Hawking computed the wrong semiclassical quantity, leading to info loss? Is the GPI well-defined for each type of theory we want to study?
- Boruch-Iliesiu-Yan'24: proposal for how to prepare and count BH microstates using the GPI, including non-perturbative corrections in $1/G_N$ (!).

Near-extremal 4D BH

- Ghosh-Maxfield-Turiaci'19 ($AdS_2 \times S^1$), Iliesiu-Turiaci'20, Heydemann-Iliesiu-Turiaci-Zhao'20.
  The near-horizon geometry of a near-extremal 4D charged BH has a long throat, described by an approximate $AdS_2 \times S^2$.
- This region can be treated separately from the exterior region where any probe is far away from the black hole and Newtonian gravity is King, and matched to it using knowledge of reflection/transmission coefficients.
- Classical near-extremal charged black holes have long been known to have a breakdown temperature, which is where emission of just one Hawking quantum would alter T_H appreciably,

$$\ell_P T_{brk} = \frac{\pi}{\ell_P M_{ext}} \frac{1}{S_{ext}} .$$

  This is very cold for astrophysical black holes. Also, the classical gravity Bekenstein-Hawking entropy behaves near extremality as

$$\frac{S(T)}{k_B} \simeq \frac{A_{ext}}{4\ell_P^2} + 4\pi^2 \frac{T}{T_{brk}} .$$

Relationship between 4D and 2D theories

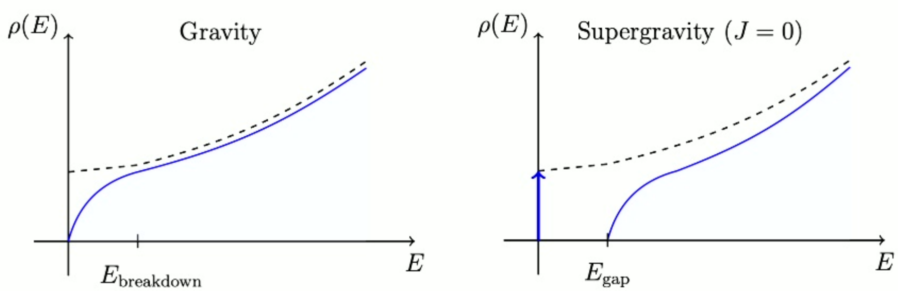
- Note that the length of the throat can be expected to have increasingly large quantum fluctuations as extremality is approached – the throat length itself becomes infinite in the limit. Backreaction is important here.
- Large diffeos of AdS_2 and rotational modes on S^2 become almost-zero modes of the BH solution, which have big strongly coupled *quantum* fluctuations.
- JT gravity is a 2D theory of dilaton gravity with a linear dilaton potential. Helpfully, it describes the dynamics of spherically symmetric fluctuations of the AdS_2 metric, and of the transverse S^2 which plays the role of the dilaton in the KK-reduced 2D theory.
- 2D matter fields result from (a) s-wave reduction of 4D light matter, (b) KK modes with nontrivial angular dependence, either from light matter or from the 4D metric. Even more helpfully, interactions between the JT dilaton and light matter are absent to leading order, making the theory solvable (!).
- In a very interesting example of universality, the "Schwarzian" boundary action coming from JT gravity in the context of the GPI is the very same theory that appears in the dynamics of the SYK model of cond-mat. (`Saad-Shenker-Stanford'19`: there is a very pretty duality between JT and SYK, with both perturbative and non-perturbative agreements.)

Quantum gravity corrections

- One interesting property of JT/SYK is that the inverse temperature behaves like a second coupling constant: quantum effects become large when T is low compared to T_{brk}. The quantum-corrected near-extremal entropy can be computed, and for $J = 0$ it has terms logarithmic in the extremal area and a T-dependent correction from the Schwarzian mode,

$$\frac{\delta S(T)}{k_B} = \frac{1}{180}\left(-n_S - 62 n_V - 11 n_F - 964\right) \log\left(\frac{A_{ext}}{4\ell_P^2}\right) + \frac{3}{2}\log\left(\frac{T}{T_{brk}}\right) .$$

- In turn, the above feeds into a changed density of states near extremality. At energies high compared to the breakdown scale, the density of states grows exponentially, as we would expect from a classical BH. But at low energies, *quantum gravity* corrections take over and it drops to zero like a square root.



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Near-extremal black hole evaporation

- Brown-Iliesiu-Penington-Usatyuk'24; Maulik-Meng-PandoZayas'25, Emparan'25, Bai-Korwar'25, Biggs'25: The evaporation of charged black holes is nothing like you remember from older literature, because of *calculable quantum gravity corrections*.
- Penington, Strings'25: Steps in evolution for macroscopic BH:-
  1. Semiclassical emission of photons and mixed gravi-photons.
  2. At around $M - |Q| \sim E_{brk}$, sheds angular momentum $J \to 0$.
  3. For $M - |Q| \ll E_{brk}$, diphoton emission, which proceeds slower.
  4. After an exponential time, emits e+/e-, jumps to $E_{brk} \ll M - |Q| \ll |Q|$.
  5. Has to settle at $J \to 1/2$, because fermionic now.
  6. At low T, now single-photon emission dominates.
  7. Emit another particle, goto 1.
  8. After many cycles, Schwinger emission eventually stops being suppressed.
  9. By the Planck scale, lose theoretical control.
- How do *primordial* near-extremal charged black holes behave?
- Note: Biggs is giving a PI Quantum Gravity seminar this afternoon at 15:30!

Further reading

- 1711.08482: G. Sarosi, "AdS_2 holography and the SYK model", 58p.
- 2006.06872: A. Almheiri, T. Hartman, J. Maldacena, E. Shaghoulian, A. Tajdini, "The entropy of Hawking radiation", 47p.
- 2210.01737: D. Harlow and 37 others, "TF1 Snowmass Report: Quantum gravity, string theory, and Black Holes", 21p.
- 2410.14414: N. Afshordi and 29 others, "Black Holes Inside and Out 2024: visions for the future of black hole physics", 221p.
- 2412.09537: G. Turiaci, "Les Houches lectures on 2D gravity and holography", 55p.
- 2412.16795: E. Witten, "Introduction to Black Hole Thermodynamics", 127p.