String modelling of black holes and holography

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Based on work in progress and
1410.5790 with Ben Burrington, Samir Mathur and Ida Zadeh,
1211.6689, 1211.6699 with Ben Burrington and Ida Zadeh;
1504.03288 with Dan O'Keeffe.

Talk slides: `http://ap.io/archives/talks/fi15/`

Context and motivation

String theory as quantum gravity

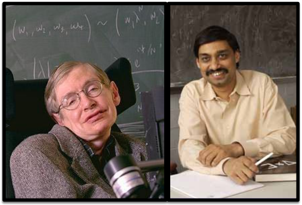
- There are multiple pathways to quantum gravity, string theory among them.

  Is there a unique quantum continuation of GR?
  Perhaps all our various different approaches will converge in the end.
- String theorists think of GR as an effective field theory. Like any other QFT, it is governed by the Wilsonian renormalization group, which describes how theory couplings change as our coarse-graining of the system becomes finer.
- GR is a mighty fine classical theory adeptly describing gravitational physics in the IR. However, like QED, it does not exist in the UV.
- String theory is very tightly constrained in the UV by internal self-consistency. Flowing this down to the phenomenologically relevant IR is intricate and *hard*. The middle ground is the difficult terrain, so people take both top-down and bottom-up approaches to elucidating the physics.

String theory and the black hole information paradox

- String theory is a powerful approach to studying both gravitation and QFTs. Has Newtonian limit. Its low-E (SUGRA) limit contains classical black hole solutions. Rich context for investigating BHs. Inherently higher-dimensional.
- Best feature: big toolbox for calculating details of how quantum gravity corrects classical spacetime. First-principles computation of S_{BH} for some BH.
- Limitation: fully realistic models of 4D astrophysical BH not yet available. String modelling of BH uses string and D-brane ingredients; supersymmetric (BPS) and near-BPS BHs are under best theoretical control.
- Hawking '75: radiation knows only about conserved quantum numbers M, J, Q. BH eat information, and unitarity is lost.
- Mathur's theorem `0909.1038`: semiclassical perturbations about Hawking's setup *cannot* rescue unitarity. Need $\mathcal{O}(1)$ changes.



- Mathur's two assumptions: (1) quantum gravity obeys strong subadditivity ($S_E(A+B)+S_E(B+C) \geq S_E(A)+S_E(C)$, where S_E is entanglement entropy); (2) each Hawking pair is created fresh from vacuum independently of others.

Questioning the effectiveness of GR

- Hawking pairs straddling horizon are max entangled: their S_E is $\ln 2$. Mathur '09: if modify quantum state about horizon perturbatively in ϵ, strong subadditivity ensures S_E keeps rising by $\ln 2 - 2\epsilon$ per new Hawking pair.
- c.f. Page's '93 theorem on S_E of subsystems: S_E between BH and Hrad grows as BH radiates, but must $\to 0$ again by time BH evaporates away, for unitarity. This needs new Hrad just outside BH to be max entangled with old Hrad.
- Monogamy of entanglement says cannot have both. L.Susskind et al. '93+ suggested BH blueshift might prevent experimenters from detecting bigamy.
- AMPS `1207.3123` refined this, igniting 'firewall' debate. Assume BH appears to distant observer as quantum system with discrete energy levels. Consider 3 postulates: (1) unitary S-matrix; (2) GR EFT works outside horizon; (3) nothing bad happens at horizon. AMPS inspected field mode excitations for infallers vs Hrad, and concluded that one of (1,2,3) must be false. "Fire!"
- Lots of proposals for avoiding firewalls (none with remnants). Harlow-Hayden `1301.4504`: quantum information theory constraints on getting info out of BH prevent them. Maldacena-Susskind `1306.0533`: 'ER=EPR' quantum wormholes. Review of BH info paradox $\supset$ firewalls by Harlow: `1409.1231`.
- Upshot: GR is less effective than we think near BH horizons.

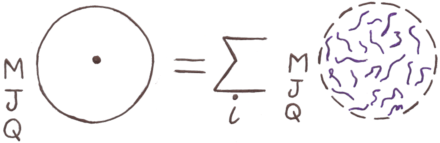
String theory tools for BH entropy and information

- String theory is not just a theory of closed/open strings. Nonperturbative *D-branes* with tension $\propto 1/g_s$ arise as loci where open strings end. They carry R-R charge and gravitate with strength $h \propto g_s N(\ell_s/r)^{7-p}$. Their gravitational scales can be made macroscopic even at weak coupling by taking large-N.
- Strominger-Vafa '96 kicked off a revolution in computing S_{BH} from quantum statistical mechanics of strings and D-branes. Their result was underpinned by a SUSY nonrenormalization theorem. This is broken at finite T, or in systems with less SUSY where degeneracy of states can jump as parameters vary.
- For certain near-BPS configurations, gorgeous multi-parameter agreement was demonstrated between spectra for Hawking emission, including superradiance, from microscopic string physics. BH greybody factors from string theory!
- What are the string theory microstates giving rise to S_{BH}? In a surprising number of cases there are classical microstate geometries, which sample S_{BH} quite well. I.Bena-N.Warner: `1311.4538`. (State of the art: 'superstratum'.)
- Caveat: getting the entropy or the emission spectrum right does not mean we get the entanglement or the quantum states right. Morally speaking, to resolve the information paradox, we need to know about the wavefunction *behind* the [putative] black hole horizon as well as in front of it.

Black hole microscopics

Microstates and the fuzzball programme

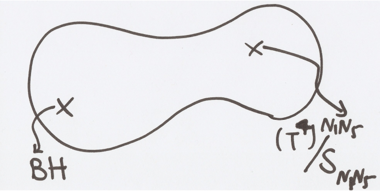
- Mathur conjectured that a BH *emerges* from thermal averaging over string theory microstates or ‘fuzzballs’ – smooth, horizonless, non spheroidally symmetric animals with the same conserved quantum numbers as the BH:



- Fuzzballs finagle traditional 4D no-hair intuition by having hair that is nonperturbative: not explained by perturbation theory about semiclassical BH.
- Large-N drives parametric enhancements of string/Planck effects, giving a string theory mechanism to support horizon-scale structure. Also: phase space of fuzzballs with macroscopic quantum numbers is exponentially large.
- **Key idea**: study gravitational fields of *quantum* string theory ingredients in natural higher-D context. (A ‘4D’ BH may not be 4D near the singularity.) Fuzzball FAQ by Mathur: `physics.ohio-state.edu/∼mathur/faq2.pdf`. Fuzzball complementarity by S.Mathur-D.Turton `1306.5488` is an attractive candidate for resolving BH info paradox. Details under active development.

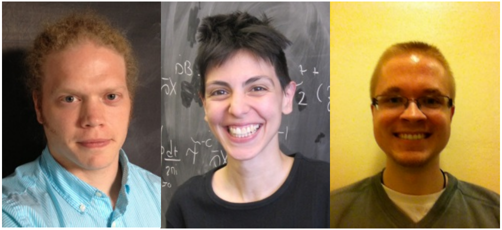
The D1-D5 system

- Prototype D1-D5 system, our focus here, is obtained by wrapping N_1 D1-branes on S^1 and N_5 D5-branes on $S^1 \times T^4$. (To make the Strominger-Vafa system, we would also add momentum $P = N_p/R$ along S^1 to make horizon macroscopic, while keeping $R(S^1)$ and $Vol(T^4)$ small to keep bulk physics 5D.)
- Which description of the physics is valid where is determined only by theory parameters, for this system. Specifically,
  - string perturbation theory works when $g_s N_1 \ll 1$ and $g_s N_5 \ll 1$;
  - SUGRA spacetime geometry is credible in the opposite limit.
- In low-energy limit with $R(S^1) \gg \sqrt[4]{Vol(T^4)}$, D1-D5 system is described by a $D{=}1{+}1$ conformal field theory living on S^1.
- The string theory D1-D5 system has a (20-parameter) *moduli space*. At one point it is best described in terms of a black hole geometry. At another, by a sigma model with symmetric product orbifold target space $(T^4)^N/S_N$ where $N = N_1 N_5$, which is a SCFT.



Deforming away from the orbifold point

- Symmetric product orbifold structure of CFT is related to physical phenomenon of *fractionation*: lowest excitation mode has energy $1/(NR)$ rather than the naive $1/R$. D1-D5 boundstate is thought of as one long multiply wound string rather than multiple singly wound strings.
- It is easy to calculate in the microscopic D1-D5 SCFT at the orbifold point where it is free. But to connect honestly with black hole physics, we need to deform the CFT away from the orbifold point towards the BH. This is the focus of three recent papers, one with Mathur, and works in progress with younger collaborators Ben Burrington (Hofstra junior faculty), Ida Zadeh (Brandeis postdoc), and Ian Jardine (Toronto PhD student).



Conformal perturbation theory

- D1-D5 CFT lives in 2D, has $\mathcal{N}=(4,4)$ SUSY, and *large* central charge $c=6N_1N_5$ (c.f. critical superstrings with $c_{\rm tot}=0$). Basic fields: Xs and ψs. $SU(2)_L\times SU(2)_R$ R-symmetry and $SO(4)_I=SU(2)_1\times SU(2)_2$ from T^4.
- In a 2D CFT, the good quantum numbers are conformal weights $(h_i,\bar{h}_i)$. Conformal symmetry completely determines dependence of 2- and 3-point functions on $(z,\bar{z})$. 3pf coefficients governed by OPE structure constants C_{ijk}

$$\mathcal{O}_i(z_1,\bar{z}_1)\mathcal{O}_j(z_2,\bar{z}_2)=\sum_k z_{12}^{h_k-h_i-h_j}\,\bar{z}_{12}^{\bar{h}_k-\bar{h}_i-\bar{h}_j}\,C_{ij}{}^{k}\mathcal{O}_k(z_2,\bar{z}_2)\,.$$

- Suppose we add a small deformation to the action of the free (X,ψ) SCFT:

$$\delta S=\lambda\int d^2z\,\mathcal{O}_D(z,\bar{z})+h.c.$$

  Conformal perturbation theory yields perturbed anomalous dimensions to first order,

$$\frac{\partial h_i}{\partial\lambda}=-\pi C_{iDi}\,,\qquad\frac{\partial\bar{h}_i}{\partial\lambda}=-\pi C_{iDi}\,.$$

  Subtlety: if there are multiple $\{\phi_k\}$ with weights $(h_k,\bar{h}_k)$, we need to diagonalize C_{iDk} in the entire block of fields with those weights.
- Our question: how do h_i change under deformation for low-lying string states?

Deformed orbifold SCFT [1211.6699 + in progress]

- For general string states this problem would be impossibly hard. But for *low-lying* string states, only a finite number of operators has the correct conformal weight to mix. So the procedure for diagonalizing to find desired anomalous dimensions will truncate in a *finite* number of steps.
- We found evidence of operator mixing at first order in λ. This makes the work quite nontrivial: all operators participating in mixing at first order need to be identified in order to find C_{iDj} to get the desired anomalous dimensions. [In progress.] How do we do such calculations in the D1-D5 $(T^4)^N/S_N$ SCFT?
- In modding out by S_N symmetry, we lose states from the spectrum. But we gain other states from *twisted sectors*, which return to themselves *up to* S_N.
- Useful concept: *twist operator*. Physically, insertion of a twist-2 operator takes two singly wound strings and twists them together into a doubly wound one.
- Lunin-Mathur technology '00,'01 gives S_N-invariant expressions for correlators by lifting to covering space. Morally, this is like using the method of images. All details of untwisting orbifold BCs for Xs, ψs are in the map, e.g. $z - z_0 = b(t - t_0)^n$ for order n twist. Fermion subtleties: branch cuts, spin fields. *Bosonization* replaces them with normal ordered exponentials of bosons, along with algebraic cocycles to ensure correct (anti)commutation relations.

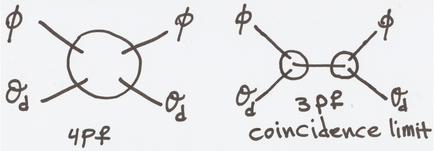
Factorization channels

- The marginal deformation we want is the *orbifold blow up* mode $\mathcal{O}_D$. $(h, \bar{h}) = (1, 1)$, singlet of both $SU(2)_L \times SU(2)_R$ and $SU(2)_1 \times SU(2)_2$.
- Method of attack: consider $\langle \phi_i(z_1, \bar{z}_1)\, \mathcal{O}_D(z_2, \bar{z}_2)\, \mathcal{O}_D(z_3, \bar{z}_3)\, \phi_i(z_4, \bar{z}_4) \rangle$ and inspect factorization channels, to figure out who mixes with whom and how strongly. This cuts number of independent 3pf we need to calculate.

  Take coincidence limit

  $$z_1 \to z_2 \,, \quad z_3 \to z_4 \,.$$

  Singularities signal intermediate quasi-primary ops mixing with ϕ_i.



- This story is more complicated than it looks because each quasiprimary field $\phi_i(z, \bar{z})$ has an infinite family of descendants under Virasoro symmetry, and the process needs to be iterated to capture multiple factorization channels.
- We are only interested in conformal families whose ancestors ϕ_j have same conformal weight as ϕ_i: they contribute to anomalous dimension of ϕ_i. Other quasi-primaries contribute only to *wave function* renormalization at first order.
- We began the study of operators that mix with $\partial X \partial X \bar{\partial} X \bar{\partial} X$ in BPZ1, BPZ2. Jardine has written Mathematica code to help automate long boring algebra.

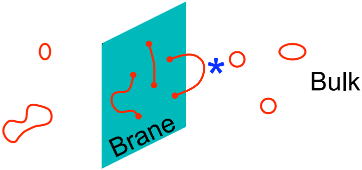
Eigenvectors and the stress tensor method [1410.0579]

- The operator mixing project is, morally speaking, about finding eigenvalues under blow-up deformation of the symmetric product orbifold SCFT towards the BH. We can also consider finding eigenvectors. More generally, we want to use deformed D1-D5 SCFT for computing a number of physical processes of interest, such as thermalization of infalling quanta.
- Our focus here: physical effect of deformation operator $\mathcal{O}_D$ on the quantum state, specifically the vacuum. A squeezed state is produced
$$\exp\left(\gamma^B_{mn}\alpha_{-m}\alpha_{-n}+\gamma^F_{mn}d_{-m}d_{-n}\right)|0\rangle\,,$$
where α_{-n} and d_{-n} are creation operators for bosons and fermions.
- We showed how a technique based on the stress tensor and the conformal Ward identity makes computing mode coefficients $\gamma^B_{mn},\gamma^F_{mn}$ quicker and more efficient, and allows handling fermions as well as bosons. We also settled some questions about the continuum limit when $R(S^1)\to\infty$.
- We made use of spectral flow, a symmetry of the superalgebra which allows mapping R sector states to NS sector states, and mapping to the cover (t-space). Result: integrating the following equation gives $\gamma^B_{mn},\gamma^F_{mn}$
$$\partial_{w_0}\left\{\sigma_2^+(w_0)|0_R^-\rangle^{(1)}\otimes|0_R^-\rangle^{(2)}\right\}=\oint_{w_0}\frac{dw}{2\pi i}T(w)\{\cdots\}\to\frac{z_0}{2}\left(L^{(t)}_{-2}+J^{3\,(t)}_{-2}\right)|0\rangle_{(t)}\,.$$

AdS/CFT holography

Why is AdS=CFT?

- Consider N_3 D3-branes. What fluctuates? Interacting open+closed strings. (D-brane dynamics is induced from open string dynamics – no extra input.)



- Open strings have endpoints living on the 3-branes. Their lowest mode of vibration is a massless spin-1 gauge boson. Low-E approx: 4D $\mathcal{N}=4$ SUSY gauge theory (which is a CFT). Closed strings live in full 10D. Their lowest mode of vibration, massless spin 2, describes the fabric of spacetime.
- Maldacena '97 discovered a low-energy *decoupling limit* which turns off the interactions between open and closed strings. On the branes, it strips away α' and g_s corrections and leaves CFT_4. In the bulk, it zooms in on near-core region of spacetime. Produces quantum string theory living on $AdS_5 \times S^5$.
- *Same* stack of 3-branes whether you think in open string *or* closed string terms. Therefore, 4D CFT is the hologram for quantum gravity in 5D AdS!

Holographic dictionary

- AdS/CFT even works when heat system up to finite T. Involves BH in AdS. (Phase transition: Hawking-Page ↔ deconfinement in CFT on S^{d-1}.)
- Holography conjecture: string theory in $AAdS_{d+1}\times S^k$ is equivalent to CFT_d:

  $$Z_{string}\left[z^{\Delta-d}\phi(x,z)|_{z=0}=\phi_{(0)}(x)\right]=\langle e^{-S+\int d^dx\phi_{(0)}\mathcal{O}(x)}\rangle_{CFT}\,.$$

  Bulk isometries match CFT symmetries. Handy AdS facts: near ∞ ($z\rightarrow 0$), area grows like vol; higher partial waves do not fall off like in AF spacetimes.
- AdS/CFT is powerful because it is a strong/weak duality: (α', g_s) corrections small when 't Hooft coupling and rank $(g_{YM}^2 N, N)$ are large, and vice versa.
- Prime example of operator dictionary: $g_{\mu\nu}(bulk)\leftrightarrow T_{\mu\nu}(boundary)$.
- UV/IR relations derived by using probes, like gravitons or open strings. Find high-energy in CFT ↔ near-boundary in bulk. So to cover all E in CFT, need whole bulk. Holographic RG flows developed, including surface counterterms.
- Nonlocal probes: correlation functions, Wilson loops, entanglement entropy. (Witten diagrams: bulk-boundary propagators and bulk vertices.)
- AdS/CFT sheds light on the question of background independence in quantum gravity. It is independent of bulk background except for its AdS asymptotics which are locked down by boundary physics.

Less symmetric holography

- Holography is applicable to systems other than 4D $\mathcal{N} = 4$ SYM. Polchinski+ 0907.0151: any CFT with a planar expansion and a sufficiently sparse spectrum of low-dimension operators should have a local AdS bulk dual.
- Sometimes in bottom-up setup we do not know $\mathcal{L}$ for dual QFT, but we can still use holography to discern universal aspects of strongly coupled systems.
- Fixing the asymptotics does not prevent you from having interesting phase transitions. They originate in interesting hair on bulk solutions. Bigger, more interesting classes of geometries available than previously imagined.
- To use holography to model real-world systems, need to break increasing degrees of SUSY and other symmetries. Big literature on this, divided into quark-gluon plasma modelling, AdS/condensed matter; also, dS/CFT.
- Breaking boost: can get residual Schrödinger or Lifshitz symmetry. Breaking anisotropy and homogeneity; modelling superconductors, Fermi surfaces, strange metals, hyperscaling violation, lattices, glasses, disorder, ...
- AdS/CFT is a fascinating laboratory for studying thermalization processes relevant to black hole physics. Study quenches and look to extract universalities, using local and nonlocal probes such as S_E.
- Holography is neat for gravity ppl: we get to *geometrize* phases of dual QFT.

Perturbatively charged holographic disorder [1504.03288]

- Collaborator for work in this section: Dan O'Keeffe (Toronto PhD student).

- Difficulty in field theory: little is known about disorder at strong coupling. Basko-Aleiner-Altshuler cond-mat/0506617: many-body localization may occur, with suppression of conductivity.
- Other works on modelling holographic disorder include: Adams-Yaida 1102.2892, 1201.6366; Hartnoll-Santos 1402.0872, 1403.4612, Hartnoll-Ramirez-Santos 1504.03324; Lucas-Sachdev-Schalm 1401.7993, Lucas-Sachdev 1411.3331; Arean-Farahi-PandoZayas-Landea-Scardicchio 1308.1920, 1407.7526. See preprint for full list.
- Build in disorder via fluctuating gauge field and solve backreacted EOM perturbatively in disorder strength, analytically. Allows study of dual transport. Solving full charged problem is hard, so focus on perturbative charging.

Perturbing about $\langle\rho\rangle = 0$

- Disorder induces a finite charge density. How is conductivity affected? Zero initial charge density means perturbing about AdS_4. We expect constant DC conductivity due to particle-hole symmetry.
- Einstein-Maxwell has enough structure to be interesting but not intractable
$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}\left(R + \frac{6}{L^2} - \frac{1}{4}F^2\right) .$$
Our EOM are (trace-removed) Einstein equation and Maxwell equation. Radial electric ansatz for the gauge field $A_t(r)$.
- Introduce disorder along one boundary direction x. Holographic dictionary says near boundary $r \to 0$, A_t behaves like $A_t(x,r) = \mu(x) + \rho(x)r + \ldots$, where $\mu(x)$ is chemical potential and $\rho(x)$ is related to dual charge density.
- Source disorder via chemical potential $\mu(x) = \overline{V}\sum_{n=1}^{N-1} A_n \cos(k_n x + \theta_n)$, where $\overline{V}$ is the (constant) disorder strength, frequencies $k_n = nk_0/N$ are evenly spaced, and θ_n are random angles uniformly distributed in $[0, 2\pi]$. k_0 defines disorder scale and is held fixed. Disorder averaging is defined by $\langle f\rangle_D = \lim_{N\to+\infty}\int\prod_{i=1}^{N-1}\frac{d\theta_i}{2\pi}f$. The A_n control correlations. For Gaussian disorder $A_n = 2\sqrt{\Delta k}$, and $\langle\mu(x)\rangle_D = 0\,,\ \langle\mu(x_1)\mu(x_2)\rangle_D = \overline{V}^2\delta(x_1 - x_2)$.

Solution strategy for $\langle \rho \rangle = 0$

- Gauge field enters at second order in Einstein eqns. First solve Maxwell eqns in initially AdS geometry to get linear order A_t, then use this to find second order backreacted geometry.
- Require AdS_4 asymptotics. Convenient to use Fefferman-Graham (FG) gauge
$$ds^2 = \frac{L^2}{r^2}\left[-\alpha(x,r)dt^2 + dr^2 + \eta(x,r)dx^2 + \delta(x,r)dy^2\right] .$$
- Perturbatively expand, e.g. $\alpha(x,r) = 1 + \overline{V}^2\alpha_2(x,r) + \cdots$ and similarly for the other metric components.
- An analytic solution is available at second order [OP2] 1504.03288.
- At first glance, disorder-averaged metric looks divergent in interior as $r \to \infty$. Happens because of breakdown of naive perturbation theory. Technique for taming secular divergences: Poincaré-Lindstedt method (adapted to scalar disorder in Hartnoll-Santos 1402.0872). Basic idea: allow contributions from additional functions which preserve AdS_4 asymptotics. Obtain $\langle \eta_2 \rangle_D = 0$ and
$$\overline{V}^2 \langle {\alpha_2 \atop \delta_2} \rangle_D = \frac{\overline{V}^2}{L}\frac{1}{k_0 L}\left[\pm\frac{1}{4} \mp \frac{1}{4}(1 - k_0 r)\exp(-2k_0 r)\right] ,$$
- Physically sensible answers for disorder-averaged metric, e.g. curvature finite.

DC conductivity

- To find $\langle \sigma_{DC} \rangle_D$ along x, adapt method for holographic lattices used by Donos-Gauntlett `1401.5077`, `1409.6875`.
- Turn on A_x perturbation linear in time $A_x = a_x(r) - Et$, where E is electric field magnitude. Linearize about perturbation. Feed this into Maxwell eqn and solve for $a_x(r)$ at leading order in $\overline{V}$. This sources perturbations in metric at next order in Einstein eqns. Solve linearized Einstein eqns for perturbations.
- Conserved quantity: current along x-direction $J^x = \sigma_{DC} E$. J^x is a function of perturbations. Since it is conserved, can evaluate it anywhere in bulk. Find J^x/E and evaluate disorder average. Obtain

$$\langle \sigma_{DC} \rangle_D = \frac{1}{16\pi G_N} \left[1 + 4 \frac{\overline{V}^2}{L} \frac{1}{k_0 L} \right]$$

- Note that this result depends on the corrected metric, so it is specific to Gaussian disorder. It would be interesting to see whether it persists for other distributions or at higher orders in perturbative disorder strength.
- How is transport affected by the implementation of disorder? There may be a larger space of available solutions to study and classify.

Finite charge density and future directions

- At finite $\langle\rho\rangle \neq 0$, our baseline is Reissner-Nordstrøm-AdS. Since this is translationally invariant on the boundary, the DC conductivity diverges. This is cured by breaking symmetry, e.g. by introducing disorder.
- A_t is non-vanishing in baseline solution, so disorder mixes baseline and 1st order perturbations, and metric functions are corrected at 1st and 2nd order. Analytic problem becomes harder because baseline charge implies that metric functions α, η, δ no longer take the form $1 + \dots$ but instead $f_{\alpha,\eta,\delta}(r) + \dots$.
- Interestingly, can still find an expression for disorder averaged DC conductivity, using horizon data and DG holographic lattice technique. Assumptions: AdS_4 asymptotics, regularity of disorder source and metric at the horizon r_0. See `1504.03288` for details.
- Numerics are likely necessary for finding metric solution. (c.f. scalar case at finite T: `1504.03324`).
- Can backreacted disorder be found for other systems, e.g. holographic superconductors?
- How about glassy dynamics, breaking of replica symmetry, and ultrametricity?
- For many-body localization, is there a holographic incarnation of transport being suppressed at critical amount of disorder?

Comments and summary

Spacetime emergence and holography

- Vector holography/higher-spin theory may provide a bridge between SUGRA and full string theory. Tower of higher-spin massless modes in AdS. HS in 3D has BH. Horizons, singularities not invariant under HS gauge transformations, but can alternatively define BH via holonomy in Chern-Simons formulation.
- van Raamsdonk conjectured `1005.3035` that smooth connected patches of bulk geometry emerge from entanglement of regions on the boundary. Recent investigations: S_E is not enough to fully probe a bulk BH, spectral information may be needed to diagnose spacetime connectedness, and emergence of an effective notion of spacetime locality may originate from coarse-graining.
- Ryu-Takayanagi conjecture `hep-th/0603001` relates information theoretic entanglement entropy S_E associated to region R in field theory to geometrical area of minimal surface in bulk whose boundary is R. RT formula explained by Lewkowycz-Maldacena in `1304.4926`, using bulk version of replica trick.
- Further recent analysis showed that the first law for S_E – for small perturbations about CFT vacuum states and ball-shaped regions – translates in the bulk to satisfaction of equations of motion linearized about AdS. Constraints were also obtained at nonlinear level, and entanglement inequalities used to derive conditions on the bulk stress tensor.

Spacetime emergence and BH microstates

- In the fuzzball approach, the focus is on microstates. They are the animals whose degeneracy is plugged into the Boltzmann formula in aiming for S_{BH}. For certain sub-classes of fuzzballs it was shown how averaging produces the BH horizon and singularity. But the status of the general conjecture is unclear.
- Microstates do not possess horizons – or regions behind the horizon! Nor do they possess infinite BH ‘throats’ that we are familiar with. Instead, they have a *finite* throat with a ‘cap’ at the end. Sticking to string theory in all regions delivers the correct Hawking greybody factors and ergoregion physics.
- Physically, a key fact is that soft Hawking modes with $E \sim k_B T$ interact with the collective modes of the microstate differently than hard $E \gg k_B T$ infalling modes which have been blueshifted in from infinity.
- How exactly will we see emergence of effective BH geometry?

Take-home messages

- GR is probably not an effective field theory of gravity near the horizon of a macroscopic black hole. Finding exactly what is wrong with the formalism is under active investigation – and has been bugging us for 40 years!
- Working with large numbers of D-branes can produce parametric enhancement of physics you thought was inherently string theoretic or Planckian out to macroscopic black hole horizon sizes.
- Not all vacua of string theory are defined by Calabi-Yau compactifications. Some, describing quantum gravity in spacetimes with AdS asymptotics, are defined by a CFT without appealing to the worldsheet.
- AdS/CFT shows us how one extra bulk spacelike dimension emerges, but generically without a path integral proof as yet. It has been applied to modelling condensed matter, the quark-gluon plasma, and even cosmology.
- In a top-down analysis, we developed symmetric orbifold technology of the microscopic D1-D5 SCFT and used techniques of conformal perturbation theory to investigate deforming towards the black hole geometry.
- In a bottom-up analysis, we modelled perturbatively charged holographic disorder in Einstein-Maxwell gravity with $\Lambda < 0$ and backreaction. We found an analytic solution at 2nd order in disorder strength, and DC conductivity.