Musings on (Space-)Time from a Gravitational String Theorist

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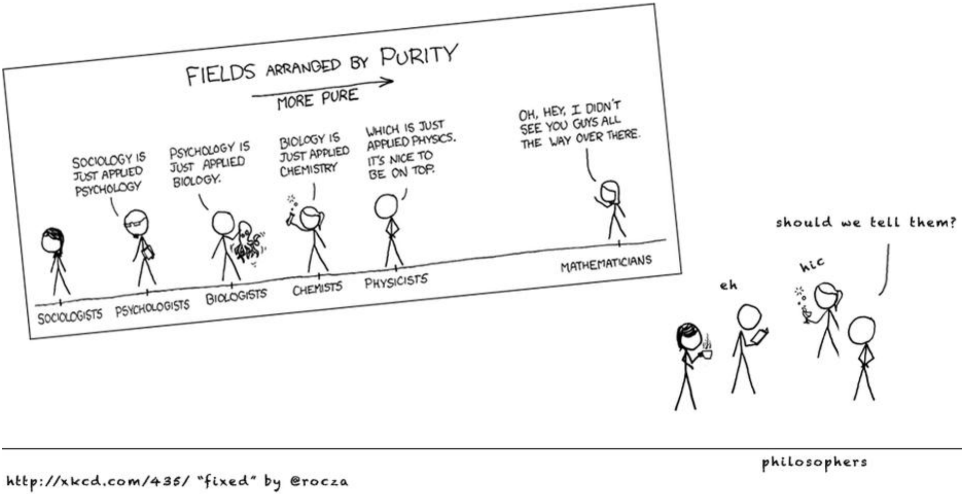
Slides: http://ap.io/archives/talks/sdphi/

String theory has sparked much progress in thinking about spacetime in the past twenty years, involving ideas like duality, D-branes, black hole entropy, the holographic AdS/CFT correspondence, and the Landscape. Two interrelated themes will be our focus: aspects of holography and microscopic string models of black hole physics. Topics will include the firewall debate about the black hole information problem and candidate resolutions, and developments in holography involving entanglement entropy, bulk locality, and higher-spin. Recent advances on both fronts have emphasized linkages between quantum entanglement and spacetime geometry, and produced better questions about the validity of GR as an effective field theory. Many big questions in the field remain open, such as the nature of time and how quantum mechanics itself might emerge.


FIELDS ARRANGED BY PURITY
MORE PURE
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY.
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS
MATHEMATICIANS
should we tell them?
hic
eh
philosophers
http://xkcd.com/435/ "fixed" by @rocza

Framing quantum gravity

Physics-philosophy nexus

- Curiosity about physics, gravity especially, will always be my prime driver. Apologies in advance for my philosophical illiteracy. $\Rightarrow$ Educate me!
- S.Hawking made headlines recently claiming that "philosophy is dead". This felt like trolling from someone with little investment in philosophical expertise.
- S.Weinberg's criticism carries more weight as he is far from ignorant about the philosophy of science. He knows of "no one who has participated actively in the advance of physics in the postwar period whose research has been significantly helped by the work of philosophers". *Why?* Is change needed?
- Physicists are in a blazing hurry to understand new phenomena and to explore utility of tools, both experimental and theoretical.
- Mathematical rigour tends to take longer to establish. Famous e.g.: Dirac δ, which physicists used for years before it was understood as a distribution.
- Philosophical interpretation tends to lag even further behind. An oft-heard frustration from physicists: "Why are philosophers still arguing about that?" e.g. for QM interpretations, decoherence is popular (e.g. 0907.0977).
- Researchers who teach know there is a mismatch b/w historical development of a subject and most efficient way to teach it. Why do we [all] sometimes wallow in confusions resolvable by adoption of superior conceptual technology?

Aesthetics

- Interdisciplinary interactions can be uncomfortable because constructing a dictionary of motivations (which often seem $\perp$ at first) is time-consuming. How can physicists and philosophers be maximally useful to each other? True interdisciplinary interactions give both parties measurable academic benefit.
- Physics fashion, too, is culture-dependent – with fluid aesthetics. Theoretical physics timescales are short, perhaps too short. It used to be that publications either side of the Iron Curtain were considered simultaneous if published within 1-2 years. Now, with `arxiv.org`, you get more like 1-2 weeks.
- Concerns about employability among the precariat limit options for career strategies. Publish-or-perish makes incrementalism strategic and speed essential. Senior string theorists tend to advise younger colleagues to avoid thinking too philosophically about quantum (space)time. D.Gross's maxim "When in doubt, calculate!" reverberates worldwide.
- What is the *right* theoretical physics aesthetic? Utility? Experimental or theoretical utility? Beauty? Mathematical beauty? c.f. E.Wigner "The Unreasonable Effectiveness of Mathematics in the Natural Sciences".
- We are judged sensitively on our sense of taste in selecting problems upon which to work. But how exactly do we teach what constitutes good taste in theoretical physics without arguing from institutional authority?

Wilsonian RG

- In his *Beyond Spacetime 1* talk, J.Harvey remarked that Loop QG people have roots in GR with major figures who like(d) to philosophize. String theorists tend to be more pragmatic. (c.f. Caltech interpretation of QM: "It works!")
- We use Wilsonian RG framework to think about the universe. GR is framed as an effective FT, not something deeper: like QED, it does not exist in the UV.
- The Wilsonian RG is the bedrock of modern quantum physics, including string theory. It tells us how couplings change as our coarse-graining becomes finer. Messing with its structural underpinnings in any way requires extreme care, in order not to break decades' worth of beautiful theory-experiment agreements.
- Within the framework of string theory, the hard part is connecting the UV, where the theory is very tightly constrained by internal self-consistency, with the phenomenologically relevant IR. Middle ground is the difficult terrain.
- Being a string theorist does not preclude bottom-up motivations. Indeed, many of the most influential string theorists have plenty of them.
- People who try to bridge the $\downarrow$ vs $\uparrow$ gap typically get the classic criticism that to be credible and employable one needs disciplinary focus. To be labelled a 'string theorist', rather than a '(super)gravity/(astro)particle theorist', a history of working with microscopic string theory tools is required.

String worldsheet

- Is there a unique quantum continuation of GR? Perhaps all our various different approaches will converge in the end, to the *right* quantum gravity.
- Practitioners of each approach are keenly aware of current limitations in our answers to Correspondence Principle questions.
- In ST, matter tells spacetime how to curve, and spacetime tells matter how to move, all in one giant equation. How to begin? Start with the σ-model worldsheet action, which treats [NS-NS] spacetime fields as *coupling functions*. Classical theory has 2D conformal invariance. Insisting on this at quantum level requires all β-functions to vanish, giving spacetime equations of motion. Obtain 10D SUGRA + perturbative corrections in both α' and g_s.
- Plus: string theory bakes in a Newtonian limit from the outset. Minus: we get $D = 10$ and other massless fields in the spectrum.
- Critics say the σ-model perturbs about a background. But fluctuations of that background are included in the analysis, so string theory has a less naive form of background independence than many people think. What form should background independence even take when there is no near-classical regime?
- Superstring dualities challenged philosophers in new ways by involving radically different sets of d.o.f. with the same underlying physics. Review: J.Polchinski 1412.5704. + As yet, no worldsheet theory of AdS/CFT.

Testiness about testability

- Working to build compactifications suitable for a universe with small $\Lambda > 0$ led to a scarily large Landscape of vacua. (But see T.Banks 1208.5715.)
- As C.Vafa pointed out in hep-th/0509212, the particle theory Swampland is even larger, because particle theory models have fewer UV constraints. So competitors lecturing us on predictability (e.g. P.Steinhardt at Strings 2014) are not standing on clearly superior ground.
- Some people claim that string theory is not falsifiable. They are wrong. Counterexample from almost a decade ago: hep-ph/0604255:-

Falsifying Models of New Physics via WW Scattering

Jacques Distler,[1,*] Benjamin Grinstein,[2,†] Rafael A. Porto,[3,‡] and Ira Z. Rothstein[3,‡]

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We show that the coefficients of operators in the electroweak chiral Lagrangian can be bounded if the underlying theory obeys the usual assumptions of Lorentz invariance, analyticity, unitarity and crossing to arbitrarily short distances. Violations of these bounds can be explained by either the existence of new physics below the naive cut-off of the the effective theory, or by the breakdown of one of these assumptions in the short distance theory. As a corollary, if no light resonances are found, then a measured violation of the bound would falsify generic models of string theory.

Interconnectedness

- One of the most compelling intellectual arguments in favour of string theory is its interconnectedness with other parts of physics and cognate disciplines. As a field, it has always had porous boundaries, both when trendy and when not.
- e.g. string theory is a heavy end-user of mathematical technologies, and it has also *driven* developments in math. It is no interdisciplinary dilettante.
- String theory is famous among beginning graduate students for having a gigantic toolbox to master. S.Shenker's theorem: that aspect of theoretical physics which you least enjoy will be what you need to know tomorrow!
- Some of the major themes of the last two decades:-
  - LHC and cosmological model building.
  - Formal aspects of string theory.
  - Formal aspects of SUSY gauge field theories.
  - Formal aspects of CFTs in various D.
  - New amplitude technologies, for QFT and ST.
  - Treasure chest of new SUGRA solutions in higher-D.
  - Holographic string/QFT dualities + applications to QGP, cond-mat, cosmology.
  - Black hole microscopics: entropy, information, and entanglement.
- D.Gross: a measure of health of the field: how many Strings 2014 talks were formal ST, and how many were something else? A: most non-formal.

Strings 2014 conference

Strings 2014

http://physics.princeton.edu/strings2014/

Broad list of topics featured:-

Mon renormalization in ST, CFT bootstrap, instability of AdS, astroparticle experiments, string inflation

Tue firewalls, holographic entanglement and geometry, entropy bounds, entropy inequalities and QFT, fuzzballs, higher-spin

Wed holographic modelling of condensed matter, nonperturbative aspects of ABJM, topological aspects of SUSY gauge theories

Thu aspects of SUSY gauge theories, gravity duals of higher-D SCFTs, mathematical ST, scattering amplitude technology in QFT and ST

Fri mathematical aspects of QFTs and STs; five vision talks

* poster session Mon, parallel sessions Wed, gong show Thu

Strominger poll: spacetime emergence

- Strominger polled dozens of us beforehand asking what we think are the key questions about string theory as a theory of quantum gravity. A selection:-

Schwarz Is there a formulation of M theory without reference to space or time? If so, what is the role of quantum entanglement?

Seiberg What is time and how does QM emerge? Given that space is emergent so should time be. Since it is hard to formulate QM without time, QM itself should be an emergent theory.

Sen What is the precise relation between quantum entanglement and classical geometry?

Freedman How much further can the present hints of a relation between entanglement and dynamical gravity be developed?

Ooguri How can one tell if a low energy effective theory cannot be completed as a consistent quantum theory of gravity? The gravity as the weakest force conjecture is a good example, but could one derive or find counter-examples to other folklores motivated by string theory?

Susskind What are the big principles we were missing whose absence prevents us from giving a definitive resolution? Answers will come from the connections between gravity and quantum information theory, in particular entanglement theory and computational complexity.

Strominger poll: holography and higher-spin

Kiritsis	Is there a way to prove the QFT/string theory correspondence?
Takayanagi	Is there any entropic meaning of internal spaces in AdS/CFT, e.g. S^5 in $AdS_5 \times S^5$, and how do they emerge holographically?
Erdmenger	Using gauge/gravity duality, can we make predictions for universal properties of further observables, e.g. those currently measured in heavy-ion collisions at LHC, or in graphene and Dirac/Weyl semimetals?
Gaberdiel	What is quantum gravity in 3D?
Vasiliev	What is the exact relation between higher-spin gauge theory and string theory?
Giombi	Do higher spin gauge theories define consistent theories of quantum gravity in general spacetime dimensions? If so, are they always related to some string theory?
Maldacena	What is general theory of weakly coupled, interacting, higher spin particles? Is string theory the only solution, like GR is only solution of a similar Q involving massless spin-2 particles and leading order in ∂s?
Rastelli	What are the universal constraints from symmetries, analyticity, and unitarity on the S matrix for quantum gravity?
Berkovits	Can twistors be used to simplify superstring theory in a manner similar to its simplication of $\mathcal{N} = 4, d = 4$ SYM?

Strominger poll: formal aspects

Gaiotto How should we define string perturbation theory in Ramond backgrounds with string-scale curvature? The pure spinor formalism works in any consistent SUGRA background.

Staudacher Will we be able to use integrability in AdS/CFT to understand the precise mechanism how strings make gauge fields and vice versa? Will this mechanism contain generic elements, which apply to the host of non-integrable instances of gauge string dualities?

Dabholkar How to compute the quantum effects in bulk gravity in AdS/CFT holography and what can we learn from them about quantum gravity?

Gubser What is the quantum theory of N M2-branes? BFSS matrix theory and ABJM theory give good handles in special limits, but the full story is unknown.

Vafa Can we develop a perturbative computational scheme for 6D CFTs?

Rastelli What is the complete list of (super)conformal field theories in various dimensions, with different amounts of supersymmetry?

Kachru Can we prove new theorems in geometry and new constraints on consistent theories of gravity using techniques of 2D CFT? Constraints of modularity, the bootstrap, and AdS_3/CFT_2 combined give one a lot of possible levers which are far from fully exploited.

Strominger poll: black holes and cosmology

Polchinski	Do old black holes have smooth interiors?
Silverstein	At what level does perturbative string theory lead to a breakdown of effective field theory in time dependent systems such as naturally formed, evaporating BH? Does it generate sufficient non-adiabatic effects in BH physics to address the firewall problem?
anon.	Why is the entropy of most BHs captured by a Cardy-like formula?
Warner	Are there large deviations from the predictions of GR at the horizon scale of the kind of black hole that lies in the cores of some galaxies: near-extreme Kerr black holes with millions of solar masses?
Bousso	What is quantum gravity in a spacetime without boundary, such as a closed universe?
Raamsdonk	What is the Hilbert space/entanglement structure of a quantum gravity state representing a cosmological spacetime, e.g. de Sitter or an eternally inflating multiverse?
Larsen	What is the microscopic origin of de Sitter entropy?
deBoer	Does the nonlocality of quantum gravity have any implications for cosmology?
Kutasov	Is there a relation in string theory between SUSY breaking and cosmic acceleration?

Black hole microscopics

String theory, D-branes, and $S_{\rm BH}$

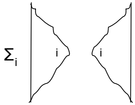
- S.Hawking 1974: quanta emitted by BH do not carry info about anything behind the horizon, other than what can be measured at infinity: M, J_a, Q_i.
- S.Mathur proved a 2009 theorem 0909.1038 (more on that soon) that subleading quantum gravity corrections cannot resolve the BH information paradox. Only order one corrections to semiclassical BH expectations around the horizon can rescue unitarity. So we need *lots* of hair. But is there any?
- No-hair folk theorems for higher-D built on intuition in $D \leq 4$ turned out to be pretty far wrong. In $D \geq 5$, there is a *much* wider variety of solutions available as ingredients for building BH. See e.g. I.Bena-N.Warner review 1311.4538.
- D-branes arise as loci where open strings end; this is enough to determine their kinematics and dynamics. Nonperturbative: tension $\tau_p \propto 1/g_s$.
- Key fact about a stack of N D-branes: for large-N, distance scales you might think are natively ℓ_s or ℓ_P can get parametrically enhanced to be as large as a BH horizon. Why? Open (closed) string corrections scale as $g_s N$ ($g_s^2 N$).
- A.Strominger-C.Vafa rocked the world in 1996 by computing S_{BH} for special $D{=}5$ BPS black holes from string statistical mechanics. This was the first computation of the Bekenstein-Hawking entropy from first principles.
- Similar methods correctly account for entropy even for rotating and *near*-BPS BHs in 5D, 4D. But a microscopic model of 4D Kerr BH remains elusive.

Emission rates and the fuzzball programme

- Morally, we need to know the wavefunction behind the horizon as well as in front of it to be able to solve the BHIP as well as compute entropy.
- String theorists got further than computing $S_{\rm BH}$. Microscopic calculations of open/closed string scattering yielded gorgeous agreement w Hawking emission from classes of near-BPS BHs, including multi-parameter greybody factors. From ST POV, '4D' BHs are hiding higher-D physics near the singularity.
- Motivated partly by new solutions, and by string CFT emission rate successes, S.Mathur conjectured in 2001 that conventional BH geometry emerges as a coarse-graining over *microstates*: non-singular, horizonless, non spheroidally symmetric geometries with same asymptotics as BH but differ inside region of order horizon size. Exponentially large density of states. Top-down POV.
- For limited classes of less-complicated fuzzballs, it is possible to check Mathur's conjecture with some rigour. Nice fuzzball FAQ by Mathur: `physics.ohio-state.edu/~mathur/faq2.pdf`.
- Mathur's 2009 theorem on BHIP used only two assumptions: (1) Hawking pairs created fresh from vacuum independently of other pairs; (2) quantum gravity obeys strong subadditivity, like any other reasonable quantum theory.
- S.Mathur also clarified in `0909.1038`, `1108.0302` that just having AdS/CFT duality does *not* resolve the BHIP in principle.

D1-D5 CFT

- Prototype microscopic model: N_1 D1-branes wrapped on S^1 + N_5 D5-branes wrapped on $S^1 \times \mathcal{M}_4$. This system has a *moduli space*. At one point it is best described in terms of BH geometry; at another, by a $D = 1 + 1$ SCFT.
- In the low-energy limit with $R(S^1) \gg \sqrt[4]{\mathrm{Vol}(\mathcal{M}_4)}$, the SCFT is a symmetric product orbifold $(\mathcal{M}_4)^N/S_N$. Related physics: strings wrapped around S^1 fractionate: lowest mode has energy $1/(N_1 N_5 R)$ rather than naive $1/R$.
- Easy to calculate in microscopic SCFT at orbifold point where it is free. And for BPS states, SUSY non-renormalization theorem ensures entropy agrees.
- But to connect honestly with macroscopic BH physics and solve information paradox, need to deform SCFT away from orbifold point towards black hole. Top-down framing. This is one focus of our research.
- Recent projects: computing anomalous dimensions of low-lying string states in conformal perturbation theory [BPZ] and analyzing aspects of squeezed states generated by twist deformations [BMPZ]. + [BJPZ in progress]
- How exactly will we see emergence of effective BH geometry? e.g.:-



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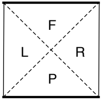

Firewalls

- Hawking pairs straddling horizon are max entangled: their $S_{\rm Ent}$ is $\ln 2$.
- Page's theorem on quantum subsystem entropy: $S_{\rm Ent}$ between BH and Hrad grows as BH radiates, but must go back to zero again by time BH evaporates away. So new Hrad just outside BH should be max entangled with old Hrad.
- But monogamy of entanglement rules out max entanglement with *two* others. Old BH complementarity of L.Susskind et al finessed this by arguing that BH blueshift prevents experimenters from seeing violation of no-xerox theorem.
- AMPS `1207.3123` pointed out new flaws in old BH complementarity, ignited firewall debate about validity of GR as an effective field theory around BHs. Consider 4 postulates: (1) unitary S-matrix. (2) EFT works outside BH horizon. (3) BH appears to distant observer as quantum system with discrete energy levels. (4) Nothing bad happens at the horizon. The main result of AMPS: one of (1,2,4) has to be false. They believe in (2) so yelled "Fire!". Technical argument was about excitation of field modes, for infaller vs Hrad.
- T.Banks had previously warned that energy may not be the only variable deciding effectiveness of GR as an EFT. Must also look at entropy.
- S.Hawking hated firewalls so much he wrote a paper basically saying that he would rather giving up on event horizons entirely! `[CBC article]`
- Recent substantial review article on BHIP $\supset$ FW by D.Harlow: `1409.1231`.

Avoiding firewalls

- Lots of papers have been written about how firewalls might be avoided. (They all differ drastically from the LQG community focus on remnants.)
- D.Harlow-P.Hayden 1301.4504: quantum information theory constraints on getting info out of a BH prevent firewalls. It takes the Page time (when $S_{\rm BH}$ drops to $\frac{1}{2}$ its initial value) to be able to do experiments detecting a firewall. Aspects of this were explained more intuitively by L.Susskind, 1301.4505.
- S.Giddings 1211.7070: a small 'nonviolent' nonlocality hidden to large scale observers may save you from firewalls. Challenge: it is generally very difficult to introduce only a 'small' amount of nonlocality theoretically.
- S.Mathur-D.Turton in 1306.5488 clarified a number of issues surrounding black hole complementarity, and explained the advantages the fuzzball approach provides in evading firewalls. The essential technical point is that a fuzzball has collective modes, and infalling quanta with $E \gg k_B T$ interact with these differently than Hawking radiation does.
- K.Papadodimas-S.Raju conjectured in 1310.6335 that the mapping of CFT operators to local bulk operators in AdS/CFT depends on the state of the CFT. Mirror operators needed for 1-sided BH, to describe behind-horizon physics in a holographic setup and avoid firewalls. So far only describes small fluctuations about a given reference state. Status: murky at best.

'ER=EPR'

- J.Maldacena-L.Susskind 1306.0533 proposed an intriguing new take on wormholes to address firewalls that has become known as 'ER=EPR'. It is built on Maldacena's proposal hep-th/0106112 that the AdS eternal BH can be constructed via $CFT_L \times CFT_R$ with thermal entanglement between L and R, built on Israel's $|\mathrm{TFD}\rangle = \frac{1}{\sqrt{Z}} \sum_i e^{-\beta E/2} |\psi\rangle_L \times |\psi\rangle_R$.
- They propose entanglements are encoded by having ER bridges, but note that these wormholes are *far* from classical. For good explanations of the proposal, see series of papers by Susskind, e.g. 1311.3335, 1411.0690.
- L.Susskind advocated in 1311.7379, 1402.5674 for connection with computational complexity: length of ER bridge $\propto$ 1/entanglement.
- 'Precursor' in boundary CFT: nonlocal object set up in boundary theory to create desired thing in the bulk in the causal future. These have played an important role in questions about avoiding firewalls. Precursors that cause firewalls are 'hard', and have exponentially large computational complexity.
- V.Balasubramanian-M.Berkooz-S.Ross-J.Simon provided some interesting caveats in 1404.6198, arguing that spectral information is also needed to diagnose spacetime connectedness in the AdS/CFT context.
- Perhaps, as Mathur has suggested, the non-classical Einstein-Rosen bridges of ER=EPR rapidly tunnel into fuzzball states?

AdS/CFT holography

Origin of AdS/CFT

- AdS/CFT holography is an equivalence between gravitational (string) theories and *non*-gravitational field theories that grew out of studying nonperturbative D-branes, which were also recruited to compute BH entropy and emission.
- Consider a stack of N Dp-branes. Because lowest mode of open superstring has spin-1 and zero mass, theory living on worldvolume of N Dp-branes is $\text{SYM}_{p+1} + \alpha'$ corrections $+ g_s$ corrections. Brane stack also gravitates.
- Maldacena's low-E 'decoupling limit' of brane stacks linked up (a) highly supersymmetric Yang-Mills theories and (b) near-horizon gravity geometries exerted by D-branes, in a kind of open-closed string duality.
  Arose by staring at near-core geometries of multiple D3, M2, M5, D1-D5.
  For more general Dp-branes, get IMSY phase diagrams `hep-th/9802042`.
  H.Nastase review of AdS/CFT basics for beginners: `0712.0689`.
- Not yet known how to do worldsheet analysis b/c R-R fields turned on.
- AdS/CFT has been applied to modelling quark-gluon plasma and cond-mat, with limited successes. Can calculate transport properties; for cond-mat the physics is quite different in spirit to the story of quasiparticles. Also inspired the study of dS/CFT correspondence where the CFT is non-unitary.
- Maldacena's AdS/CFT gives definition of asymp. AdS Lorentzian QG in AdS, by using well-understood Wick rotation in CFT and duality (twice).

Holographic dictionary

- Holography conjectures ST/QG in asymptotically $AdS_{d+1} \times S^n$ is equivalent to CFT: $Z_{\rm string}\left[z^{\Delta-d}\phi(x,z)|_{z=0} = \phi_{(0)}(x)\right] = \langle e^{-S+\int d^dx\phi_{(0)}\mathcal{O}(x)}\rangle_{\rm CFT}$. Useful AdS facts/tools: near ∞, area grows like vol; partial waves don't fall off; Fefferman-Graham expansion. Bulk isometries match CFT symmetries.
- This is not just a zero-temperature equivalence. Asymptotically AdS BH $\leftrightarrow$ turning on finite T in CFT. E.Witten:the Hawking-Page transition from BH to hot AdS is dual to the deconfinement transition in the boundary theory.
- Prime example of operator dictionary: $g_{\mu\nu}$(bulk) $\leftrightarrow$ $T_{\mu\nu}$(boundary). Second order bulk PDEs yield two solutions. Non-normalizable modes $\leftrightarrow$ changing $\mathcal{L}$ of boundary CFT. Normalizable modes $\leftrightarrow$ turning on VEVs.
- UV/IR relations derived by using probes, e.g. gravitons or open strings. Find high-energy in CFT $\leftrightarrow$ near-boundary in bulk. Holographic RG: running understood via bulk Hamilton-Jacobi, including counterterms.
- Nonlocal probes: correlation functions, Wilson loops, entanglement entropy. Witten diagrams: bulk-boundary propagators and bulk vertices.
- AdS/CFT shows us how one extra bulk spacelike dimension emerges, but generically without a path integral proof as yet. It also does not show us how time emerges. That may require going beyond QM as we currently know it.

Less symmetric holography

- AdS/CFT sheds light on the question of background independence in quantum gravity. It is independent of bulk background except for its asymptotics which are locked down by boundary physics.
- 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.
- Fixing the asymptotics does not prevent you from having interesting phase transitions originating in interesting hair on the bulk solutions. There are much bigger, wilder classes of geometries available than previously imagined.
- Holography is applicable to systems other than $\mathcal{N} = 4$ SYM. Sometimes in a bottom-up setup we do not know what the dual QFT is, but we can still use holography to discern universal aspects of strongly coupled systems.
- Breaking boost: can get residual Schrödinger or Lifshitz symmetry. Breaking anisotropy and homogeneity. Modelling superconductors, glasses, strange metals, Fermi surfaces, hyperscaling violation, disorder. Holographic lattices. My interest in holography is more bottom-up. Recent papers were on Lifshitz BH [BBP] and HSV crossovers [OP]. + [OP in progress]
- Neat part about holography from the point of view of someone interested in gravity: *geometrizing* phases of the dual QFT.

Higher-spin/vector holography

- Higher-spin theory is a lab that may provide a bridge between classical gravity and full quantum ST. Tower of modes. (c.f. ABJM, multi-M2, localization.)
- Old theorems had put stringent constraints on low-E scattering in flat spacetime that forbid $m = 0$ particles with spins $s > 2$ from participating in any interacting QFT. But in AdS, $\Lambda < 0$ provides dimensional coupling and IR cutoff, which can reconcile HS gauge symmetry w equivalence principle, giving M.Vasiliev's nonlinear unfolded equations of motion. Review: 1404.1948.
- J.Maldacena-A.Zhibodaev 1112.1016 showed why for 3D CFT with higher-spin symmetry you get a free theory, found for the dual of Vasiliev higher-spin theory in AdS_4. S.Giombi-X.Yin AdS_4 VH review: 1208.4036.
- R.Gokapumar-M.Gaberdiel 1207.6697 found the dual for AdS_3: a minimal model coset CFT_2 with $\mathcal{W}_N$ symmetry at large-N. (Scalar accompanying graviton and HS fields in 2D GG duality is massive; for AdS_4 it is massless.)
- GG actually got even further: they found that higher-spin in AdS_3 is a subsector of string theory, in the tensionless limit. Technically important.
- Higher-spin theory in 3D has BHs 1208.5182. Existence of horizons and singularities is not invariant under HS gauge transformations, but can define via *holonomy* if use Chern-Simons formulation of 3D gravity, e.g. 1302.0816.

Bulk locality

- AdS/CFT is a fascinating laboratory for studying process of thermalization. Study quenches, try to extract universalities. Review: 1103.2683.
  (Strong time dependence is harder than weak or none.)
  See also fluid/gravity correspondence; review by Hubeny: 1501.00007.
- (A.Hamilton-)D.Kabat-G.Lifschytz-D.Lowe showed in hep-th/0506118, hep-th/0606141, 1102.2910 how local operators in the AdS bulk can be represented via *smeared* operators in the CFT. Only regions in the causally relevant zone contribute. Their construction can be obstructed if there are bulk normal modes with exponentially small near-boundary imprint, such as for the AdS black hole 1304.6821. Is bulk locality emergent?
- M.vanRaamsdonk conjectured 0907.2939, 1005.3035 that smooth connected patches of geometry emerge from entanglement of regions on the boundary.
- Entanglement may not be enough to fully probe bulk geometry, esp. if BH. 1406.5859 by BCCdB discussed entanglement shadows and entwinement. Key Q: how much information can you ever reconstruct from the boundary?
- A.Almheiri-X.Dong-D.Harlow 1411.7041 argued that localization of bulk information should be understood in terms of quantum error correction. E.Mintun-J.Polchinski-V.Rosenhaus 1501.06577 connected this to boundary gauge invariance, suggesting it is closely connected to spacetime emergence.

Geometrization of entanglement

- S.Ryu-T.Takayanagi conjecture hep-th/0603001 relates the entanglement entropy S_{Ent} associated to a region R in the field theory to the area of the minimal surface in the bulk whose boundary is R. The holographic RT formula is important because it connects a geometrical bulk computation with an information theoretic field theory computation. Reviews: T.Nishioka-S.Ryu-T.Takayanagi 0905.0932, Headrick 1312.6717.
- An explanation of the RT formula was provided by A.Lewkowycz-J.Maldacena in 1304.4926, using a bulk version of the replica trick.
- 'Hole-ography' method computes entanglement for a hole in AdS spacetime 1310.4204 V.Balasubramanian-B.Chowdhury-B.Czech-J.deBoer-M.Heller. Uses differencing of RT formula, residual entropy.
- N.Lashkari-J.Simon in 1402.4829 argued that emergence of an effective notion of spacetime locality originates in restricting to a subset of observables unable to resolve black hole microstates from the maximally entangled state.
- People e.g. 1312.7856 also found that the first law for S_{Ent} – for small perturbations about CFT vacuum states, for ball-shaped regions – translates in the bulk to satisfaction of equations of motion linearized about AdS! Constraining the nonlinear story: 1405.3743. Also, entanglement inequalities can be used to derive conditions on bulk $T_{\mu\nu}$: 1412.3514.

Outline:-

Framing quantum gravity

- Physics-philosophy nexus
- Aesthetics
- Wilsonian RG
- String worldsheet
- Testability
- Interconnectedness

BH microscopics

- D-branes + counting $S_{\rm BH}$
- Emission rates + fuzzballs
- D1-D5 microscopics*
- Firewall controversy
- Quantum information theory,
- 'ER=EPR' wormholes

Strings 2014 conference

- Breadth of topic list
- Strominger's poll re big Qs: spacetime emergence,
- AdS/CFT holography,
- formal aspects of ST,
- black holes + cosmology

AdS/CFT holography

- Origin of AdS/CFT
- Holographic dictionary
- Less symmetric holography*
- Higher-spin/vector holography
- Bulk locality
- Geometrizing entanglement

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