Firewall on a Tabletop

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Quantum Gravity in the Lab

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Our charge

The purpose of the conference is to bring together physicists from diverse theoretical and experimental fields … with the goal of creating a new branch of physics. We could call it "The Theoretical and Experimental Physics of Massive Entanglement, Quantum Chaos, and Complexity," or as I prefer, "QG in the L."

What is likely to be most appreciated is the broad outlines, motivations, and explanations of concepts and new tools.

[*Lenny's instructions to the speakers*]

Why quantum gravity?

Erect a complete theory of all fundamental interactions.

Resolve deep puzzles about quantum black holes.

Understand the early history of the universe.

Learn broader lessons applicable in other contexts.

“Use gravitational intuition to understand complex emergent quantum phenomena.”

It’s fun.

What (some) others mean by "quantum gravity in the lab"

222 years since Cavendish (judged impossible by Newton).

Detection of primordial gravitational waves from inflation.

Dumb holes: Hawking radiation and supersonic flow.

Gravitationally induced entanglement between test masses.

Deformation of uncertainty relations in an oscillator ("probe the Planck scale").

Gravitationally driven intrinsic decoherence (Penrose/Diósi).

What we're learning

Geometry emerging from entanglement (RT).

Connected geometry from *uncoupled* entangled systems (M)

Spacetime as a quantum error-correcting code (ADH).

No exact global symmetry in the bulk (HO).

Fast scrambling and bounds on chaos (MSS).

Relating geometry and computational complexity (S).

Holography in simple contexts (SYK).

Insights regarding e.g. quark-gluon plasma, strange metals, …

What’s still lacking (incomplete list!)

Further elucidation of the AdS/CFT code.

Sub-AdS locality.

Asymptotically flat space and de Sitter space?

Measurements inside black holes (“state dependence”)?

What happens when you fall into a black hole (complexity of the dictionary)?

What happens at the singularity?

How hard is it to simulate bulk quantum gravity with a quantum computer?

What theories have *useful* holographic duals?

Exciting progress on the information problem

Computation of the Page curve, including the scrambling time (P, AEMM).

Quantum extremal surface defines entanglement wedge (EW).

Universal subspace quantum error correction (alpha-bits, HP).

State-dependent vs. state-independent decoding of Hawking radiation.

Interior encoded in the exterior: no need for firewalls.

It’s hard to make a firewall!

Smooth horizon of the two-sided black hole (TFD).

One-sided: black hole complementarity on steroids (ER=EPR).

Plausibly, the Hawking radiation emitted by an old black hole is *pseudorandom*. (Hawking was *almost* right.)

Which implies (Kim, Tang, JP): Encoded black hole interior that is inaccessible to computationally-bounded exterior observers.

Black hole microstates: the key that unlocks the pseudorandom state.

Exponentially powerful quantum computers can tear spacetime apart.

Implications of pseudorandomness regarding complexity of dictionary.

How can experiments help?

Probe bulk geometry by measuring *boundary entanglement* structure.

Probe *bulk locality* by measuring commutators of nonlocal boundary operators, perhaps by studying linear response.

Study the formation and evaporation of a *black hole in the bulk*; evolution of an excited state on the boundary.

Probe *fast scrambling* behavior with OTOCs (NMR, ion traps, atoms in cavities, superconducting circuits, …). Lyapunov spectrum.

Measure higher-order quantum gravity corrections.

Holographic dictionaries beyond AdS.

Traversal of a wormhole in the bulk as coherent teleportation between two boundaries (“Wormhole tomography”). Wormholes that are not semiclassical? Multipartite entanglement?

Simulating Quantum Dynamics

Classical computers are especially bad at simulating quantum *dynamics.* Quantum computers will have a big advantage.

But …

Many-body localized (MBL) systems, which equilibrate slowly, are only slightly entangled, and may therefore be easy to simulate classically.

Systems with strong quantum chaos (obeying the eigenstate thermalization hypothesis = ETH), become highly entangled and are therefore hard to simulate classically. But they are boring – they quickly converge to thermal equilibrium and after that nothing interesting happens.

To get an interesting answer, you should ask an interesting question! (Theorists can pretend to be experimental physicists!)

Digital vs. Analog quantum simulation in the NISQ era

What hard problems can we solve with (noisy) analog simulators? All-to-all coupling and noise resilience are desirable.

What is the potential advantage of digital in the NISQ era?

Simulating time evolution is expensive (Trotter and and other methods). Fault-tolerance may be necessary for illuminating results.

Digital provides more flexible Hamiltonian and initial state preparation. We can use hybrid quantum/classical methods.

Experience with near-term digital simulators will lay foundations for fault-tolerant simulations in the future (applies to NISQ more broadly).

Today's analog simulators: For example, snapshots of fluctuating string order in the doped Hubbard model, classified using machine learning (*Greiner group*). Spectral response for a strongly coupled Fermi gas (*Zwierlein group*). Quantum many-body scars (*Lukin group*). Etc.

Simulation of quantum field theory

45 years since Wilson!

Real-time evolution, nonzero chemical potential, …

Circuit-based too expensive for now?

Laying the foundations for more revealing future work.

What’s classically hard? Processes that produce highly entangled states, e.g., multiparticle production, quench, …

Stepping stone to quantum gravity.

New concepts and insights?

Where can we go in 10 years (and beyond)?

[Your suggestions here]

"Using gravitational intuition to understand emergent phenomena."

"What quantum many-body systems have *useful* holographic duals?"

-- Realistically, our goal in the near term should be to light the way toward future progress by developing new tools, methods, and insights.

-- Today's research can hasten the arrival of a new era in which quantum technology fuels remarkable advances in fundamental physics.

-- Progress will rely on vibrant discussions bridging communities, facilitated by exciting meetings like this one!