Entanglement, Complexity, and Tensor Networks

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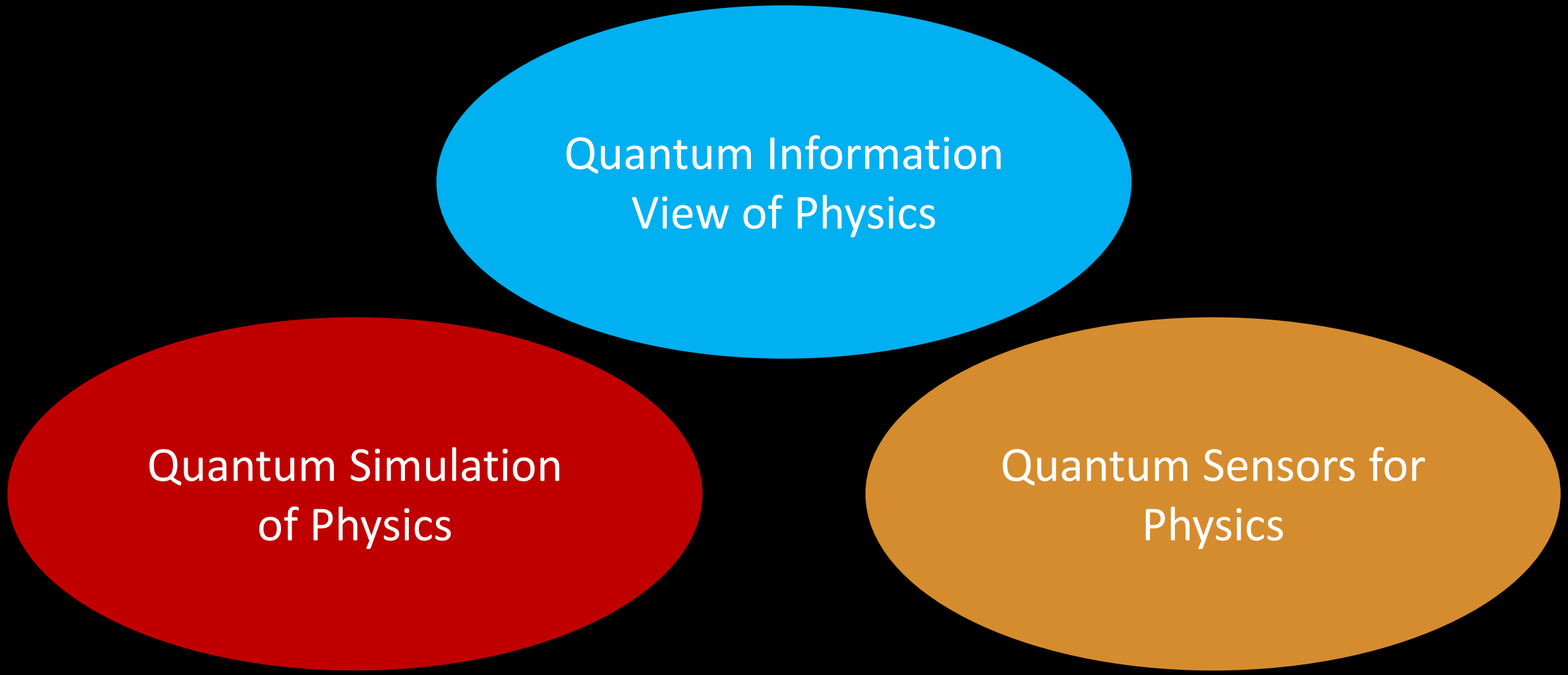
The Role of QIS in HEP

Snowmass Community Planning Meeting

October 6, 2020

Context: QIS and HEP



Some HEP Challenges

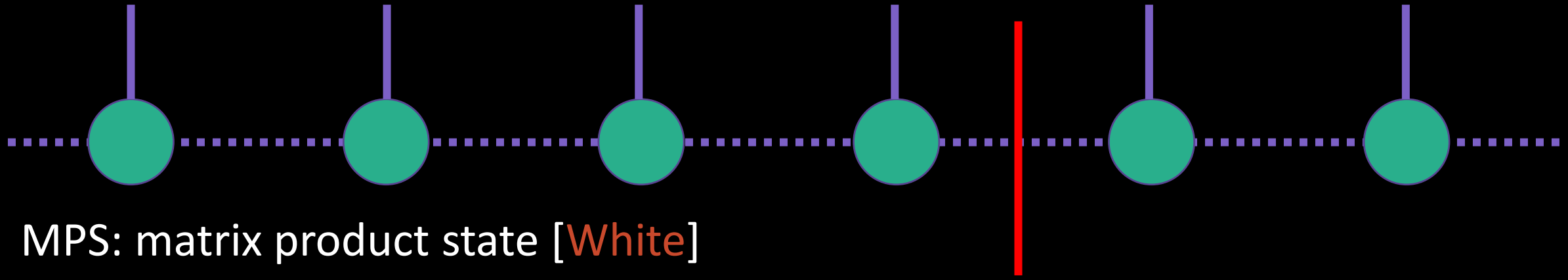
- Physics at strong coupling, esp. with a sign problem in Monte Carlo
- Dynamical situations with many active degrees of freedom
- Continuum limit and physics across many different scales

- These challenges are broadly shared with the condensed matter and AMO communities; in my view, QIS has had a greater impact in those contexts because cutoff scale physics is more directly relevant

Conservation of difficulty? No!

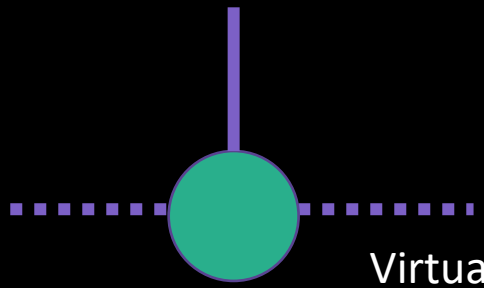
- We organize our thinking about physical phenomena in a variety of ways, including by scale, by particle/material, by force, etc.
- Claim: QIS provides a rather different way of organizing our thinking about physics, and it provides a host of powerful concepts and tools
- Conservation of (difficulty + understanding) is closer to the truth

Example 1a: Cutoff-scale mass gap

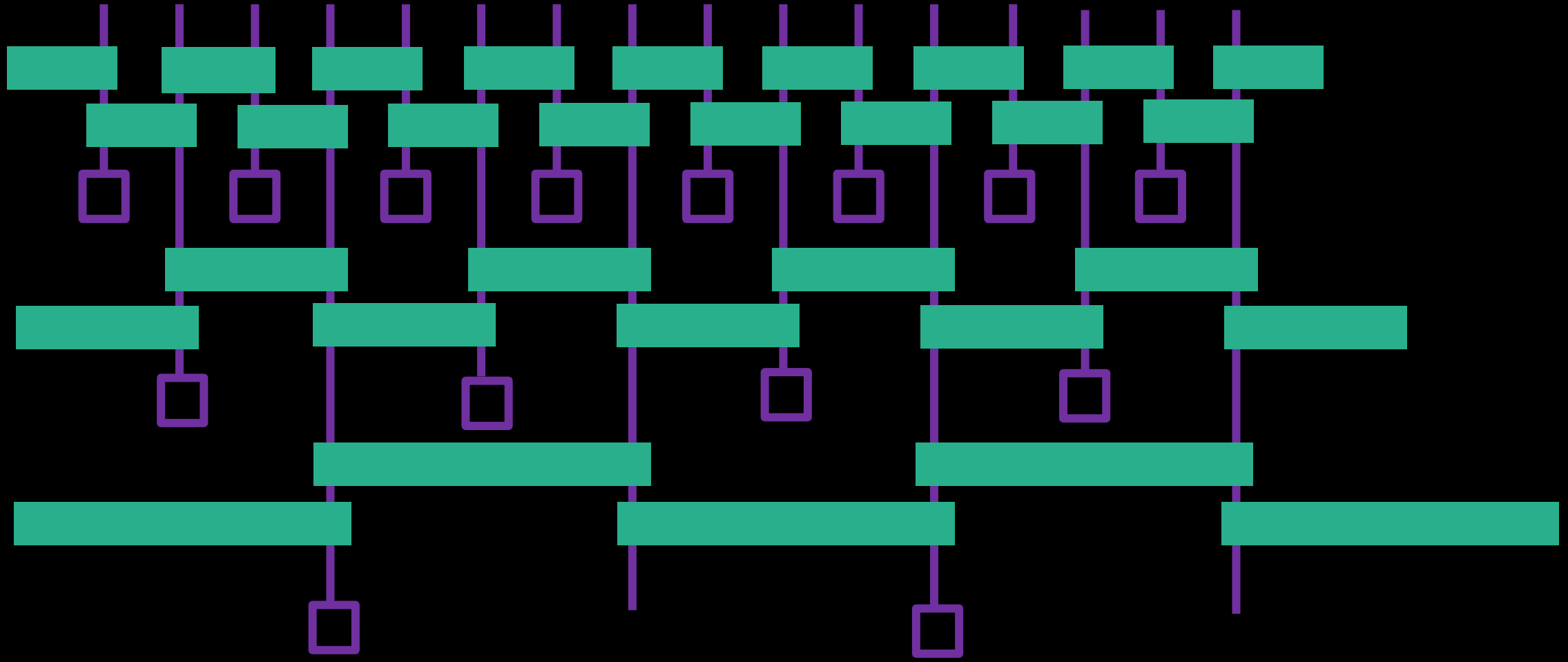


MPS: matrix product state [White]

Entanglement Area Law



Example 1b: No mass gap



MERA: multiscale entanglement renormalization ansatz [Vidal]

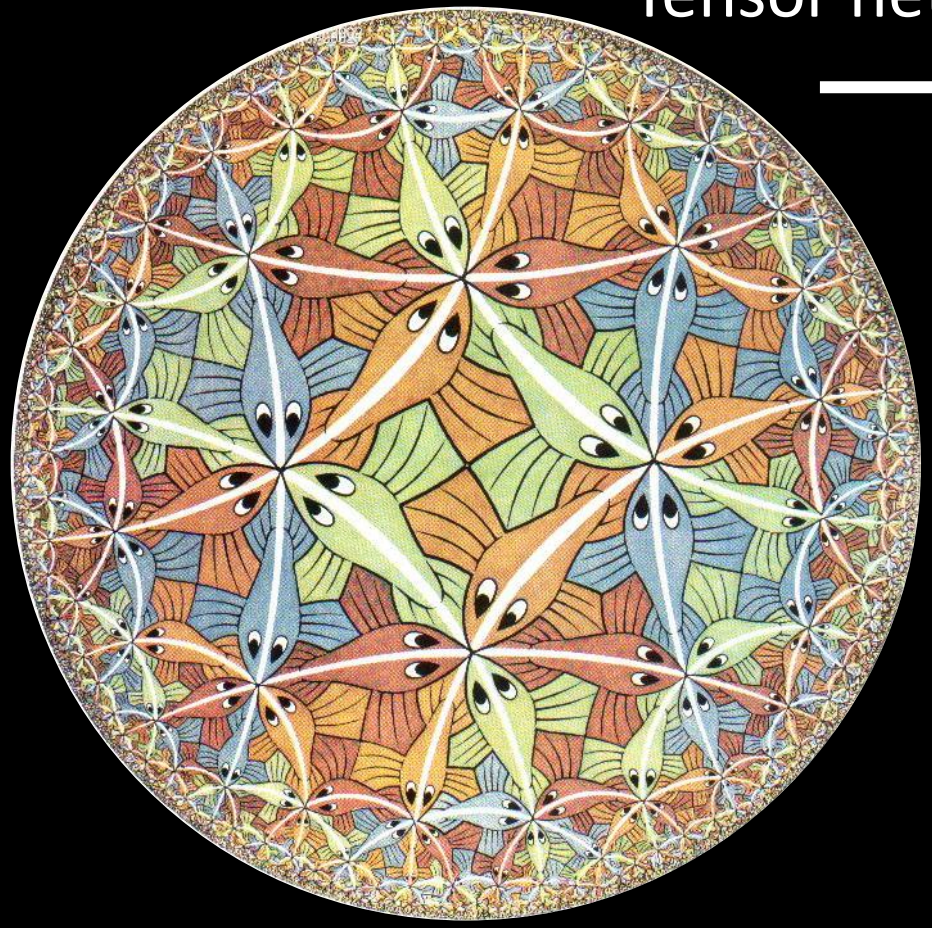
Comments

- Can give world-best variational energies, conformal data, …
- Direct connection to quantum simulation, complexity estimates
- Additional applications: correlation functions [Witteveen et al.], Wilson lines?, …
- Extensions to 2d etc. exist [Cirac-Verstraete PEPS, …], although they have additional challenges
- Symmetries and gauge structures can be incorporated

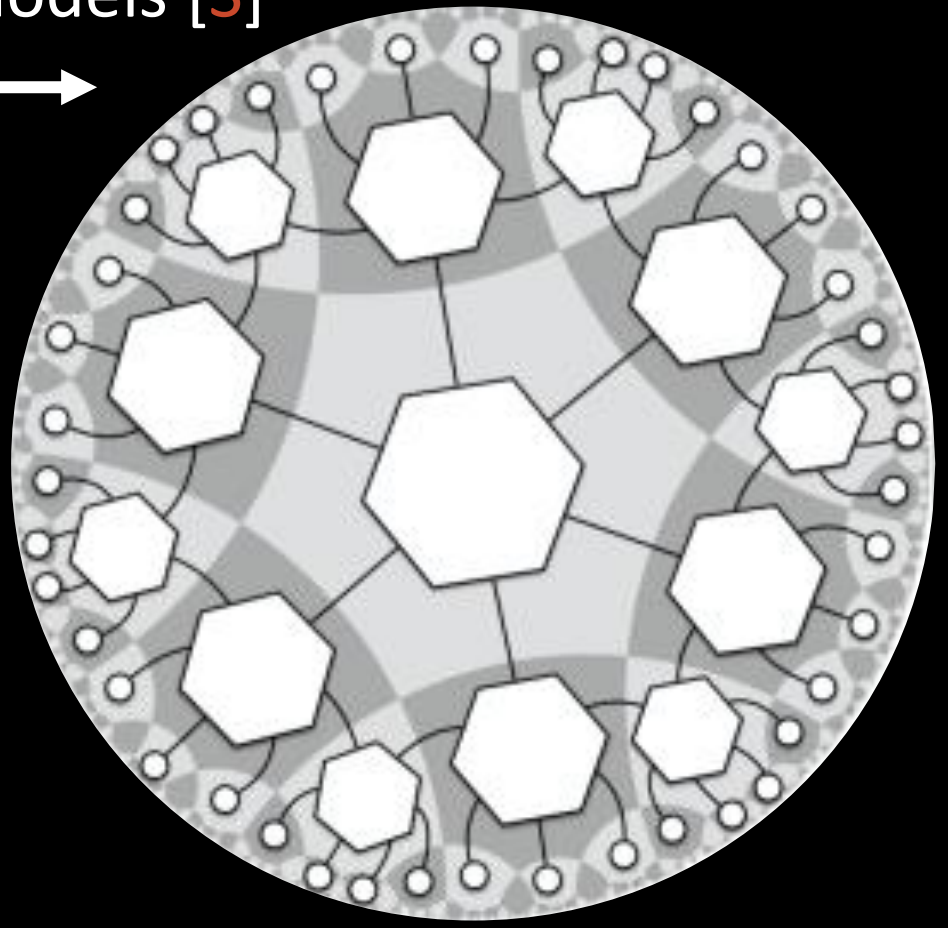
- Opportunities for major progress:
  - Higher dimensions
  - Continuum limit (multiscale physics)

Example 2: Holographic Ground States

Tensor network models [S]



Spatial Geometry of AdS [Escher]



Holographic Code [HPPY]

Comments

- Tensor networks at least provide a toy model of AdS/CFT, but they can also give technically insightful models of entanglement phenomena in AdS/CFT, e.g. random tensor networks [Hayden et al., Jia-Rangamani]
- Tensor networks also give insight into the growth of black hole interiors, the onset of chaos, the switchback effect, and the complexity of decoding Hawking radiation

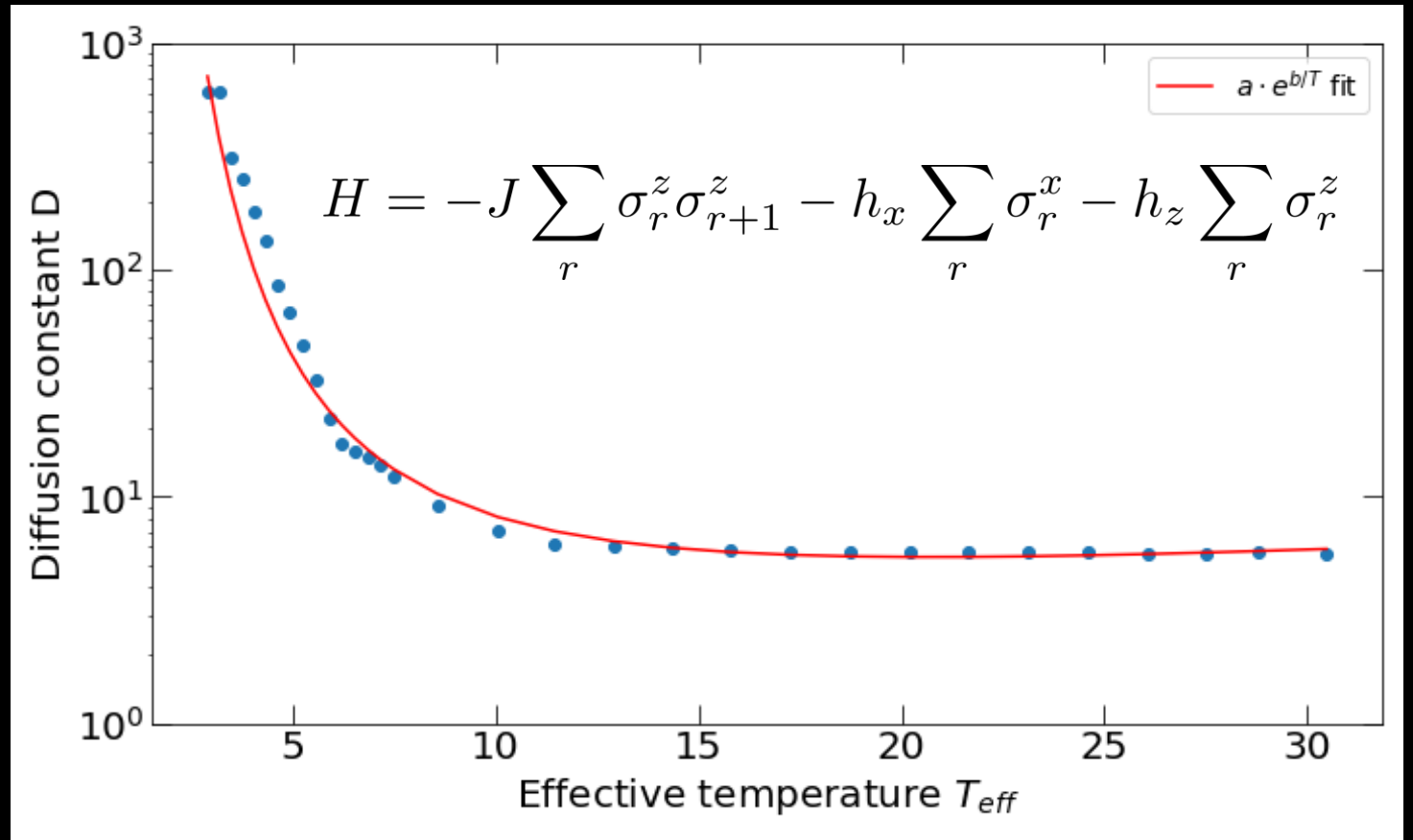
- Opportunities for major progress:
  - Symmetries, correlations, and gravitational back reaction
  - Spacetime approach (focusing less on spatial slices)

Example 3: Transport and Hydrodynamics

energy current

T_L T_R

Bath drives current, strong coupling is OK, decoherence controls the calculation



[S-Zanoci]

Comments

- Variety of methods (primarily QIS-based) give increasingly robust control of transport at the cutoff scale
- There are early attempts to access long-wavelength physics, clearly should one incorporate understanding from ground states, e.g. MERA
- How to properly coarse-grain unitary quantum dynamics? Many ideas are being studied, but no clear framework yet …

- Opportunities for major progress:
  - Accessing low energy, continuum limit physics
  - Higher dimensions

Please feel free to reach out with questions

- Entanglement, complexity, and tensor networks have:
  - Powerfully impacted cond-mat and AMO
  - Played a key conceptual role in holography (complete with backreaction on QIS, e.g. teleportation protocols and novel codes!)
  - Shown considerable promise for a variety of HEP problems
- Can we create a powerful new joint framework for HEP and QIS?
  - Quantum field theory provides a framework for HEP but does not always expose QIS properties
  - Tensor networks provide a framework for QIS but struggle with the continuum and spacetime-centric view
  - Fusing them is a grand challenge (they share principles, e.g. locality)