Quantum Networks: A Frontier for Condensed Matter Physics

Vedika Khemani
Stanford University

National Academy CMMRC Meeting

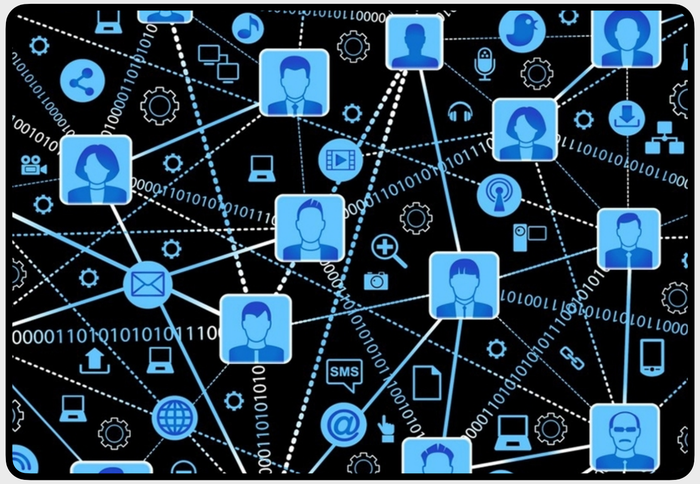
NETWORK: *A system of* ***interconnected elements*** *representing the* ***organization*** *and/or* ***flow*** *of information, resources or other entities*

Transportation Network

Greenwich Village Society for Historic Preservation

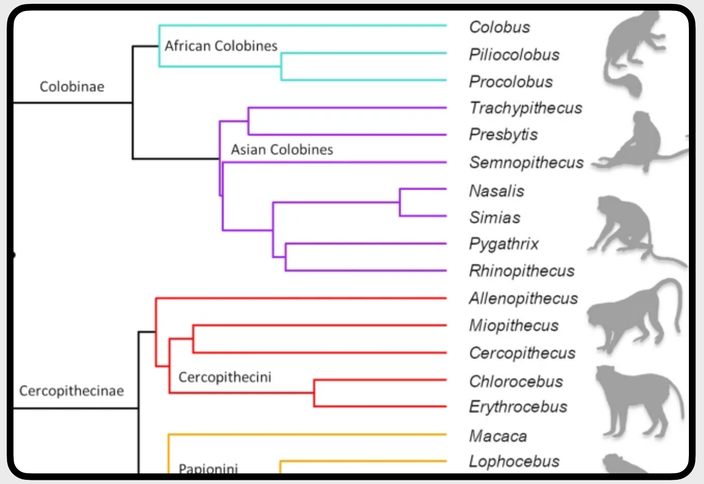
Satellite Network

Anterovium- Alamy Stock Photo



Social Network

Stefanie Koperniak, MIT News 2016



Phylogenetic Network

Sci Rep 12 (2022)

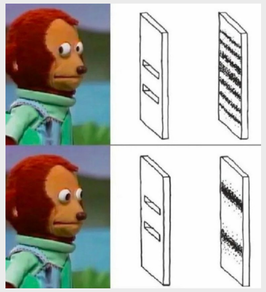
NETWORK: *A system of* ***interconnected elements*** *representing the* ***organization*** *and/or* ***flow*** *of information, resources or other entities*

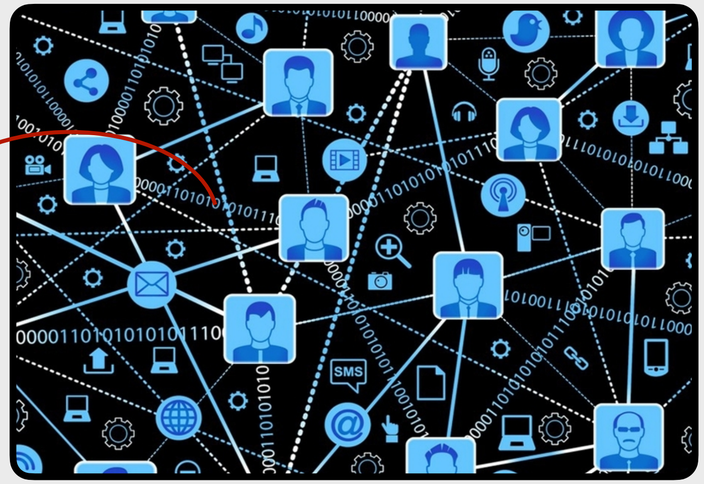
Transportation Network

Greenwich Village Society for Historic Preservation

Satellite Network

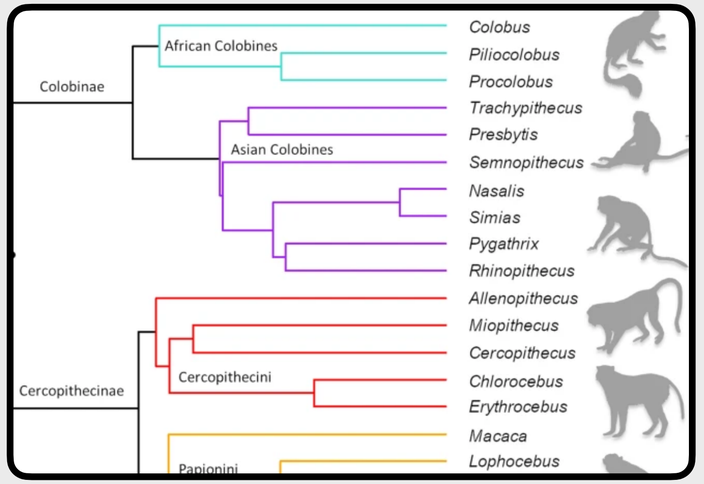
Anterovium- Alamy Stock Photo





Social Network

Stefanie Koperniak, MIT News 2016



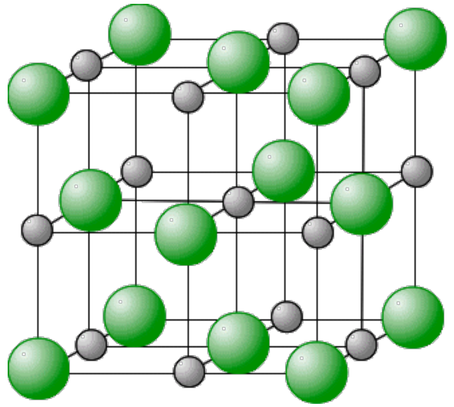
Phylogenetic Network

Sci Rep 12 (2022)

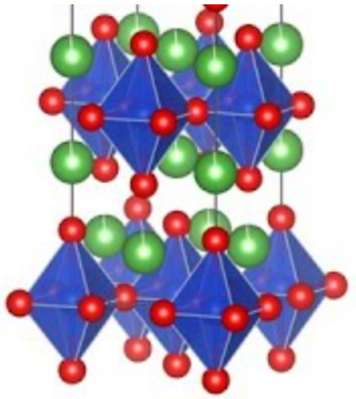
QUANTUM NETWORK

A system of many strongly-interacting quantum elements organized into different structures

All matter arises from interacting electrons self-assembling into some structure: atoms, molecules, crystals, glasses, topological insulators, superconductors…



NaCl table salt



La_2CuO_4 cuprate superconductor

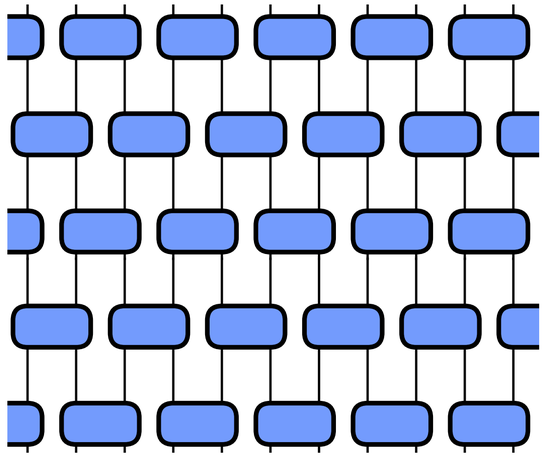
QUANTUM NETWORK

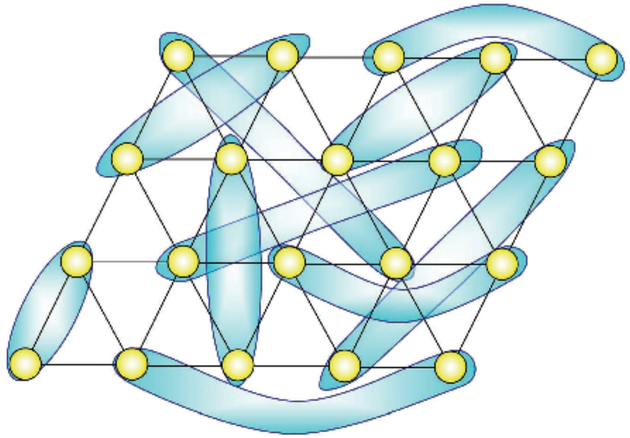
A system of many strongly-interacting quantum elements organized by the ***structure of quantum information***

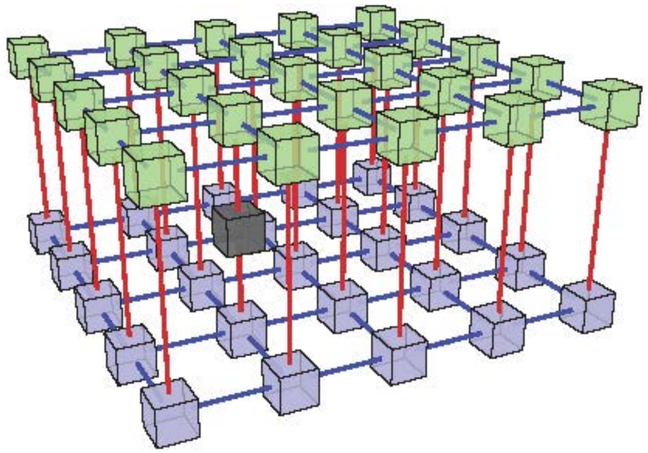
c2000s— characterize ground state phases by structure of long-range entanglement.

Unitary circuits and tensor networks are powerful for encapsulating this entanglement structure

Xiao-Gang Wen, Ignacio Cirac, Frank Verstraete…







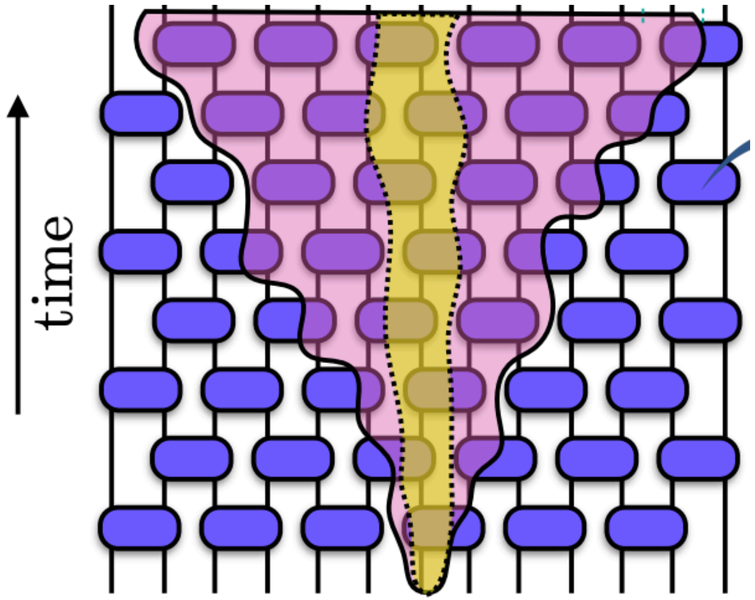
IPAM tensor network workshop 2021

QUANTUM NETWORK

*A system of many strongly and **controllably interacting** quantum elements organized by the **structure and flow of quantum information***

QUANTUM NETWORK

*A system of many strongly and **controllably interacting** quantum elements organized by the **structure and flow of quantum information***



Fisher, Khemani, Nahum, Vijay ARCMP 2023

Dynamics: flow of quantum information through spacetime

How does an isolated quantum system reach thermal equilibrium under its own dynamics?

Can a system evade thermal equilibrium?

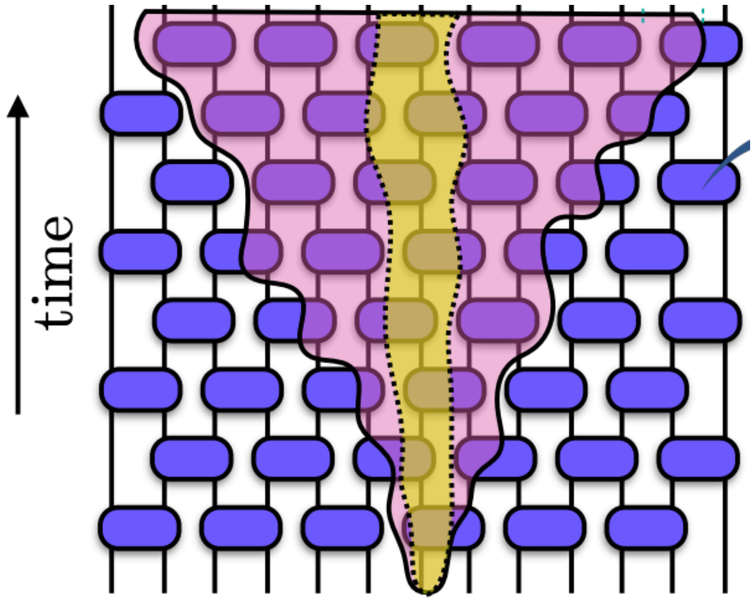
What intrinsically non-equilibrium phases of matter exist?

How do we characterize the capacity of a quantum network to retain coherent quantum information?

How do we characterize the computational capacity of a quantum network?

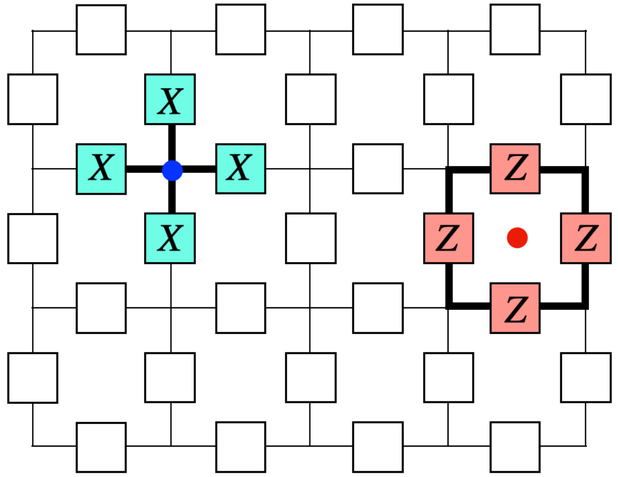
QUANTUM NETWORK

*A system of many strongly and **controllably interacting** quantum elements organized by the **structure and flow of quantum information***

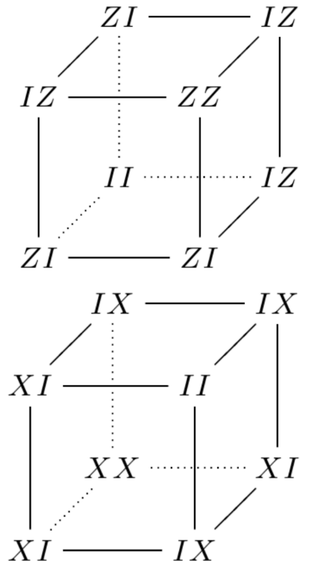


Fisher, Khemani, Nahum, Vijay ARCMP 2023

Dynamics: flow of quantum information through spacetime



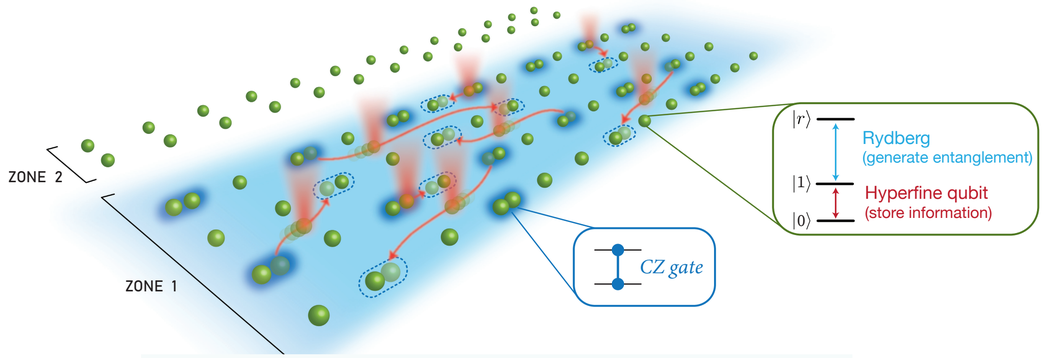
Kitaev's toric code
$\leftrightarrow Z_2$ spin liquid

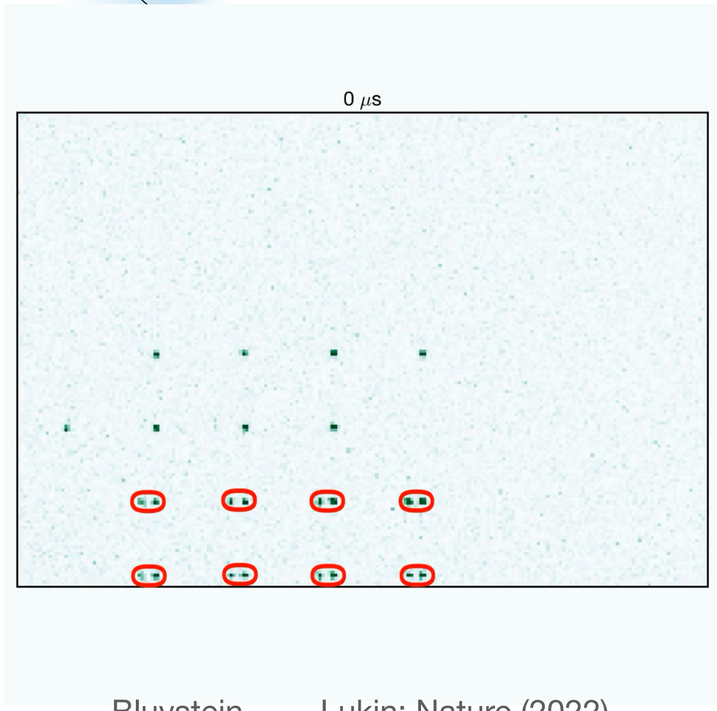


Haah's cubic code
$\leftrightarrow$ fracton phase

Engineered interactions
(new exotic phases)

Controllable Geometry and Interactions

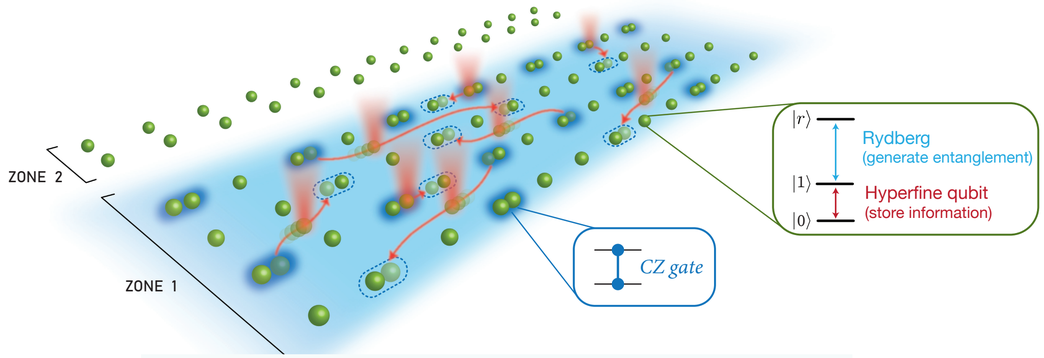


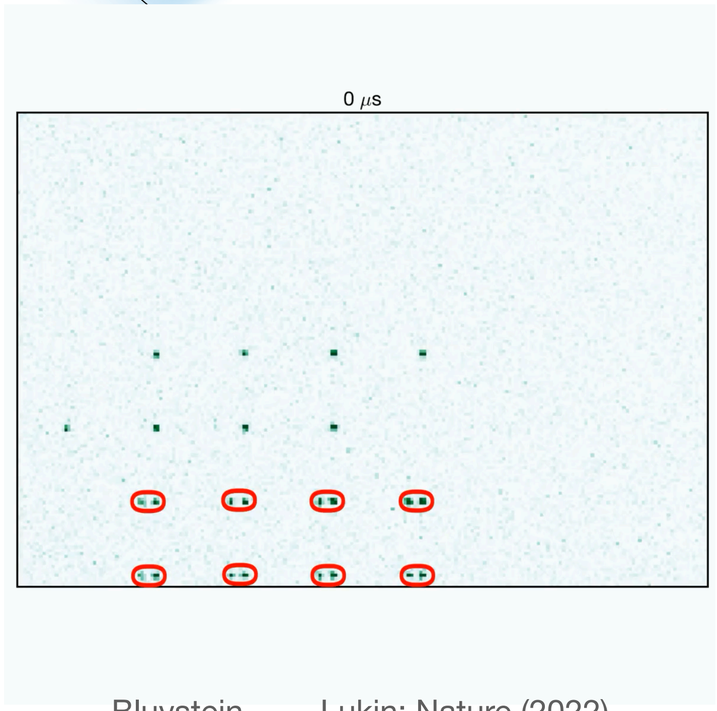


Bluvstein, … , Lukin: Nature (2022)

Manetsch…Endres (2024)

Controllable Geometry and Interactions

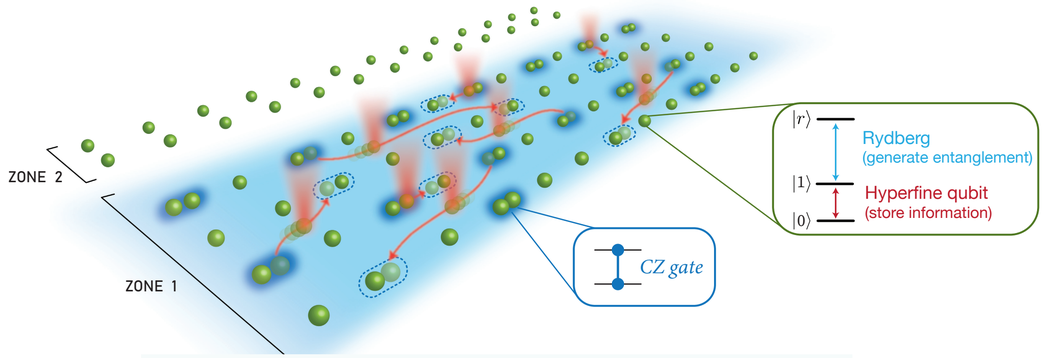


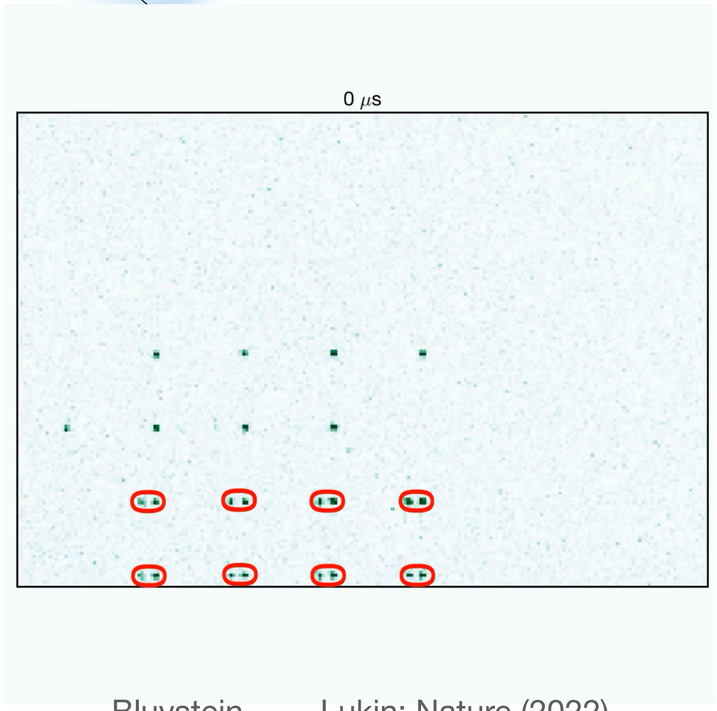


Bluvstein, … , Lukin: Nature (2022)

Manetsch…Endres (2024)

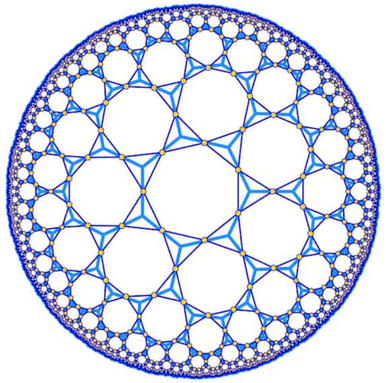
Controllable Geometry and Interactions

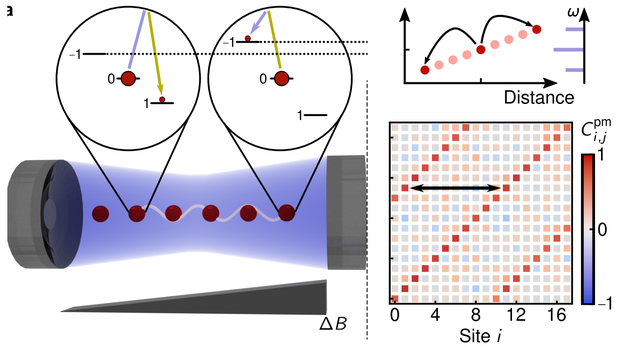


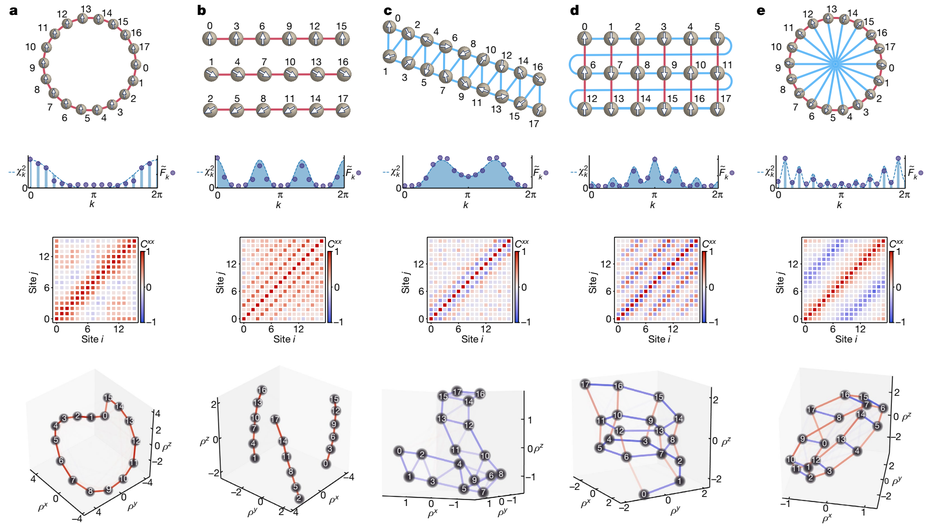


Bluvstein, … , Lukin: Nature (2022)

Manetsch…Endres (2024)



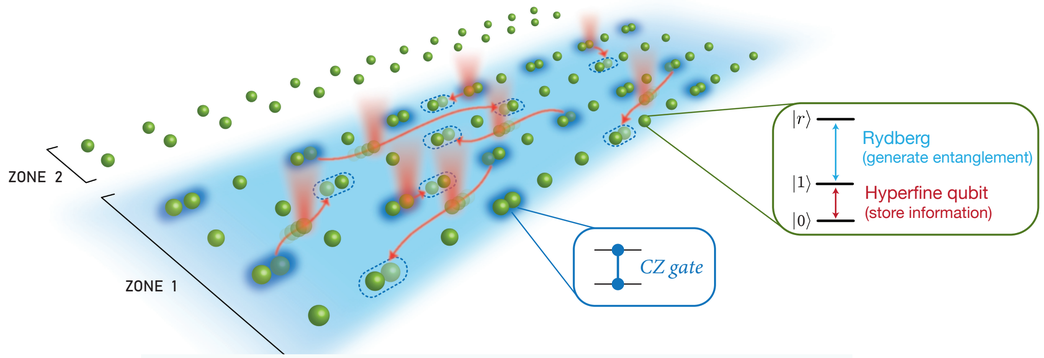


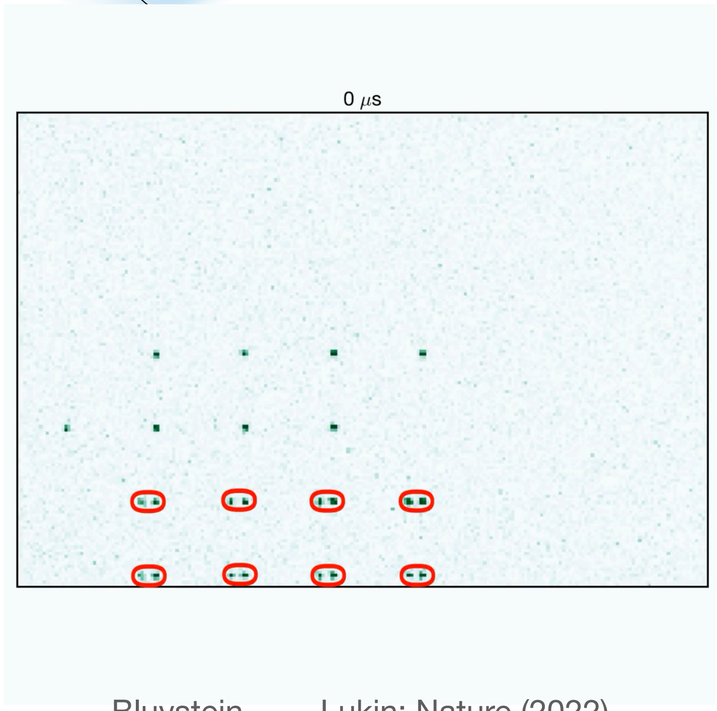


Kollár, Fitzpatrick, Houck: Nature (2019)

Periwal,…,Schleier-Smith: Nature (2021)

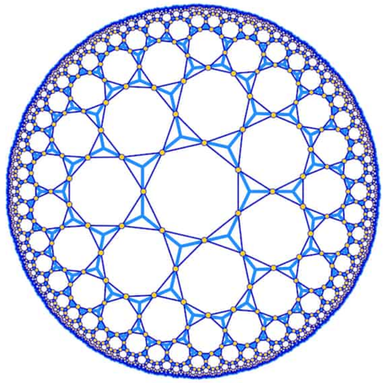
Controllable Geometry and Interactions

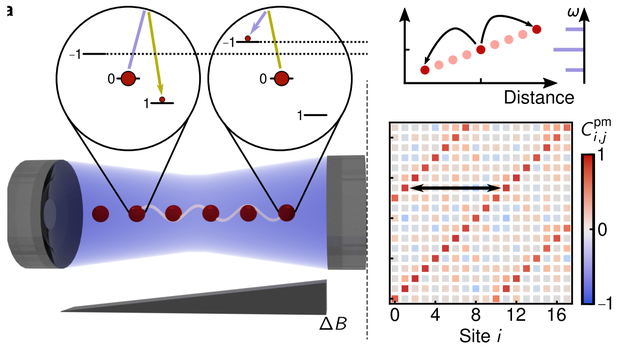


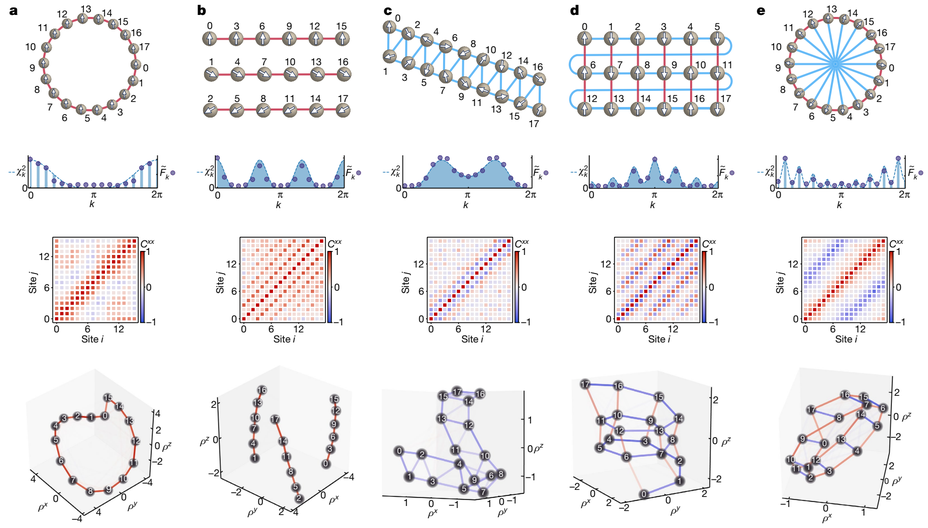


Bluvstein, … , Lukin: Nature (2022)

Manetsch…Endres (2024)





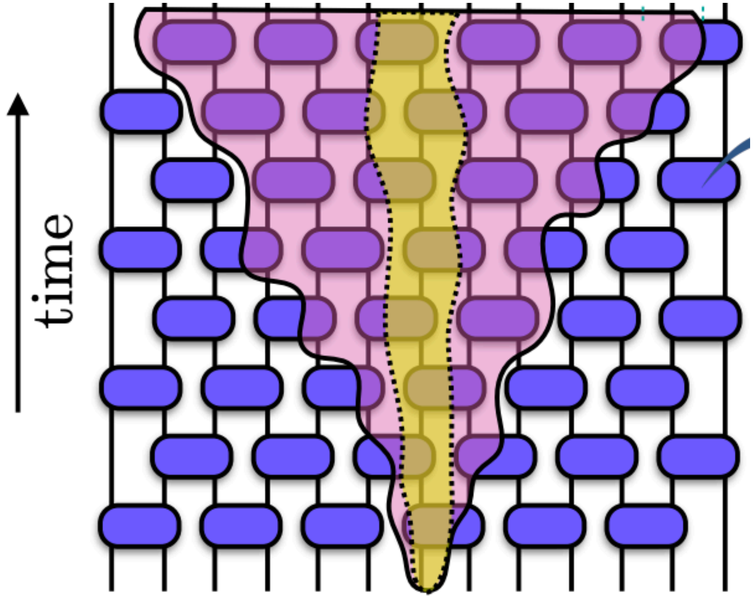


Kollár, Fitzpatrick, Houck: Nature (2019)

Periwal,…,Schleier-Smith: Nature (2021)

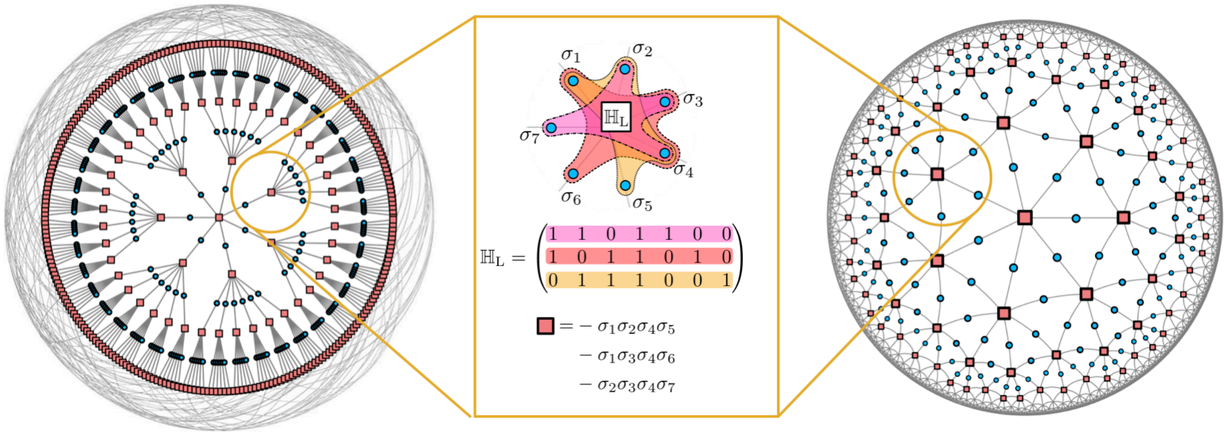
QUANTUM NETWORK

*A system of many strongly and **controllably interacting** quantum elements organized by the **structure and flow of quantum information***



Fisher, Khemani, Nahum, Vijay ARCMP 2023

Dynamics: flow of quantum information through spacetime

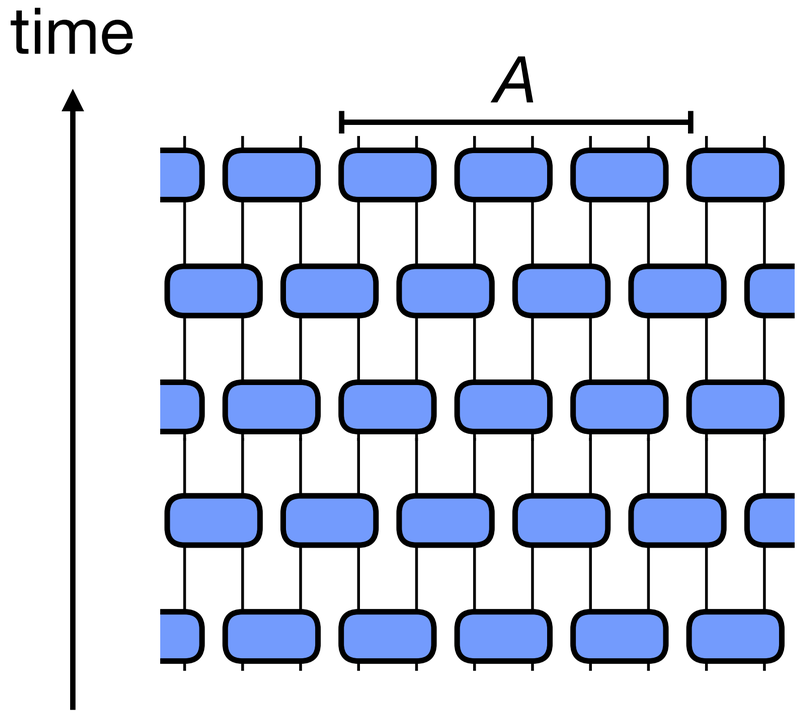


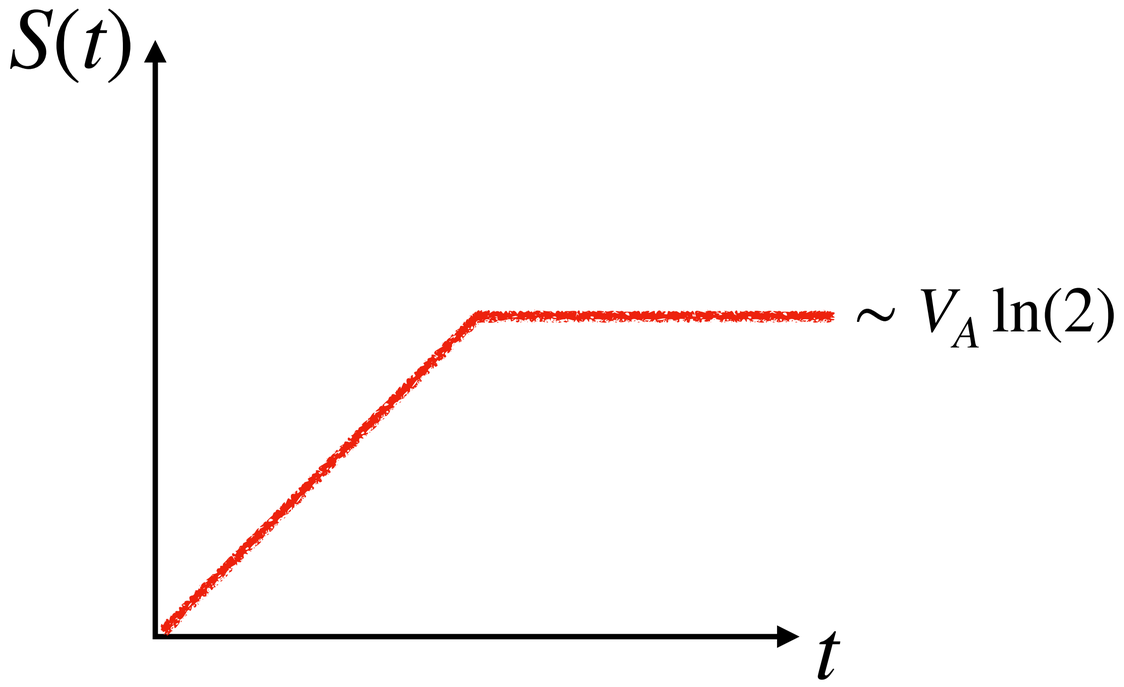
“good LDPC codes”

Engineered interactions and geometry (new exotic phases)

Universality in Quantum Dynamics

Generic strongly-interacting isolated quantum systems are expected to thermalize: i.e. to evolve to entropy maximizing thermal states





Generic strongly-interacting isolated quantum systems are expected to thermalize: i.e. to evolve to entropy maximizing thermal states

… interesting universality in the *approach* to thermal equilibrium:

Generic strongly-interacting isolated quantum systems are expected to thermalize: i.e. to evolve to entropy maximizing thermal states

… interesting universality in the *approach* to thermal equilibrium:

Dynamics of Entanglement

Nahum, Ruhman, Vijay Haah PRX 2017+ …

Dynamics of Information Scrambling

Nahum, Vijay Haah PRX 2017;
von Keyserlingk, Rakovszky, Pollmann, Sondhi PRX 2017+…

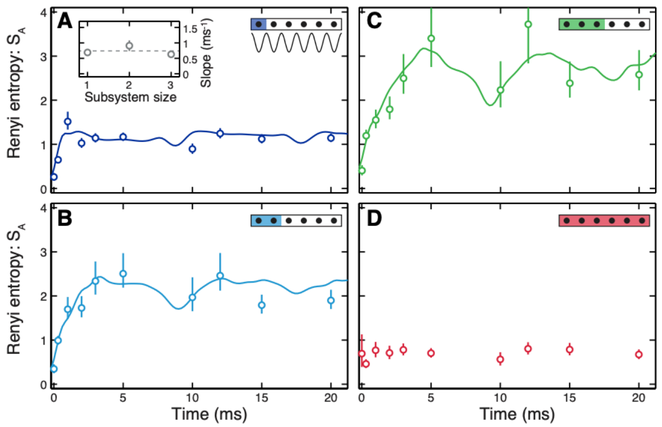
Emergence of Hydrodynamics

VK. Vishwanath, Huse PRX 2018;
Rakovszky, Pollmann, von Keyserlingk PRX 2018+…

Generic strongly-interacting isolated quantum systems are expected to thermalize: i.e. to evolve to entropy maximizing thermal states

… interesting universality in the *approach* to thermal equilibrium:

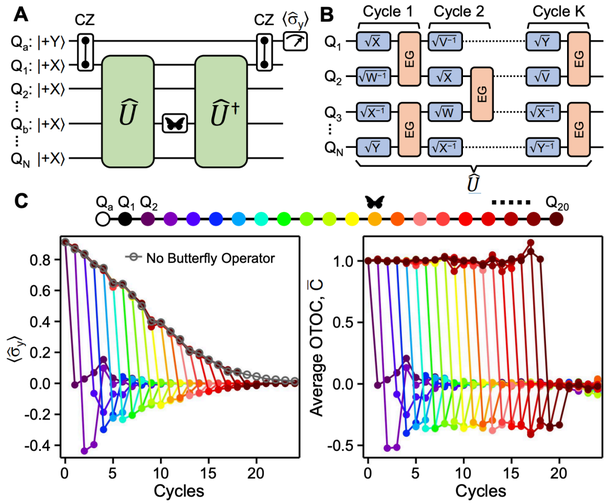
Dynamics of Entanglement



Kaufman…Greiner Science 2016

Nahum, Ruhman, Vijay Haah PRX 2017+ …

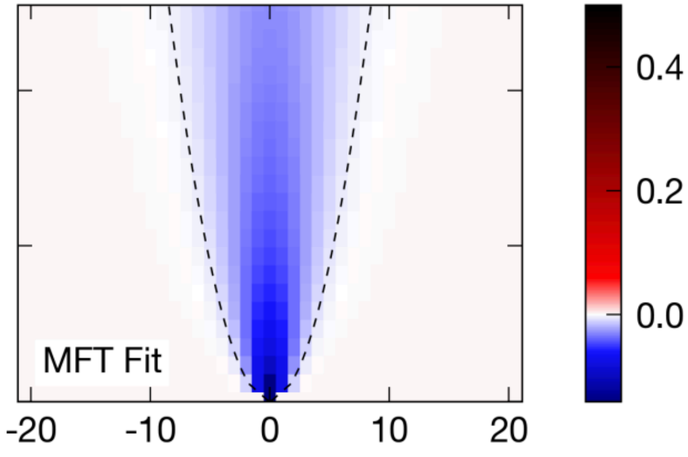
Dynamics of Information Scrambling



Google Quantum AI Science 2021

Nahum, Vijay Haah PRX 2017;
von Keyserlingk, Rakovszky, Pollmann, Sondhi PRX 2017+…

Emergence of Hydrodynamics

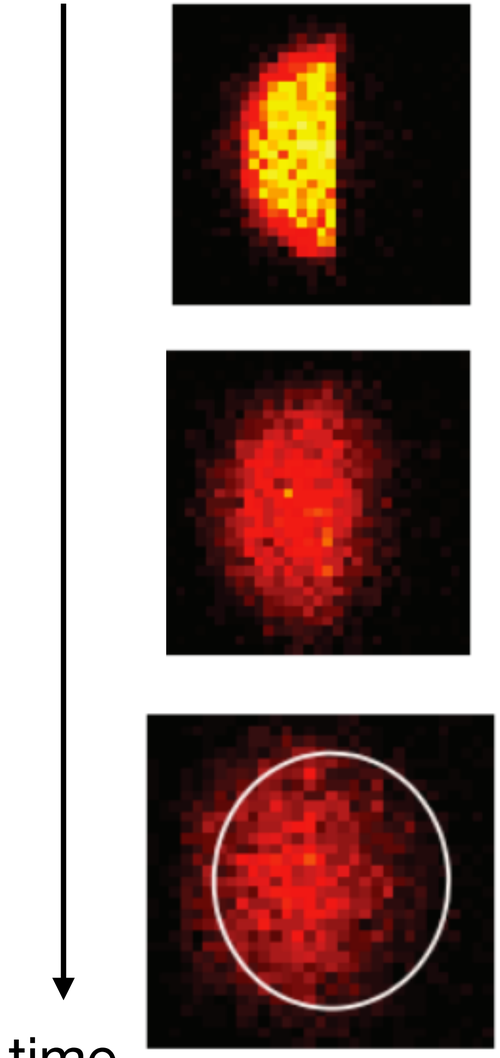


Weinand…Gopalakrishnan… Bloch 2023

VK. Vishwanath, Huse PRX 2018;
Rakovszky, Pollmann, von Keyserlingk PRX 2018+…

Universal Non-Equilibrium Phases by Evading Thermalization

I. Many Body Localization

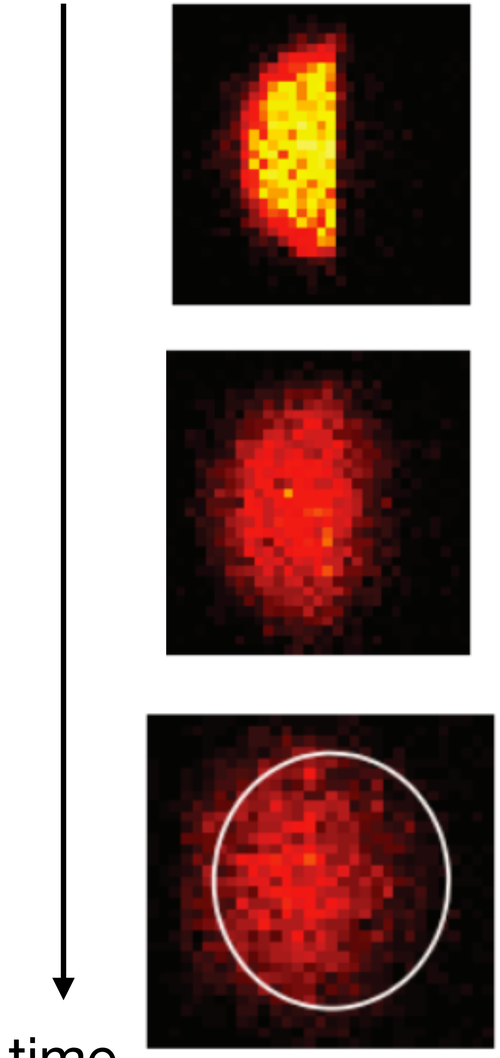


Choi…VK…Bloch,
Gross, Science (2016)

Anderson 1958; Basko Aleiner Altshuler 2006; Oganesyan Huse 2007 + …

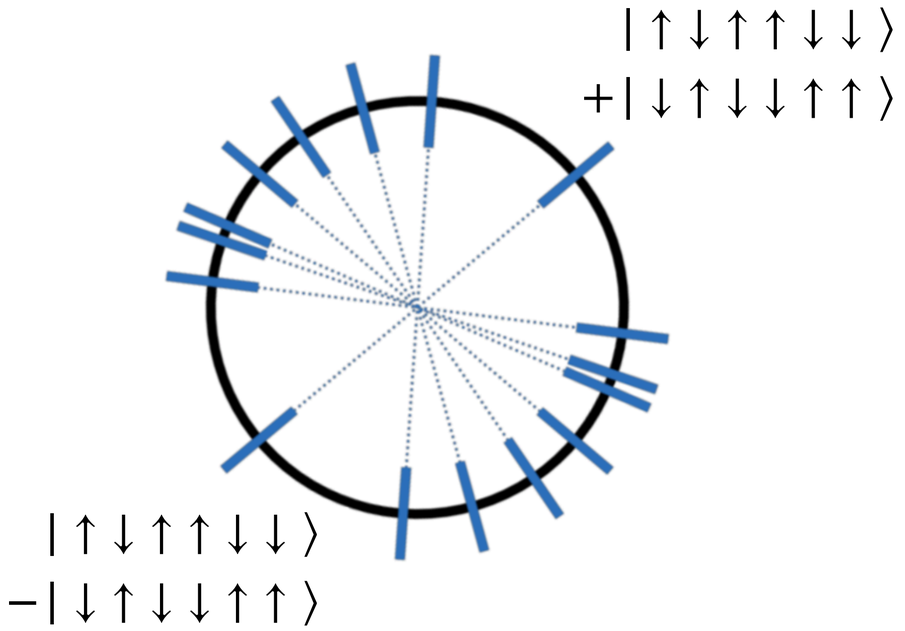
I. Many Body Localization

MBL Floquet Phases



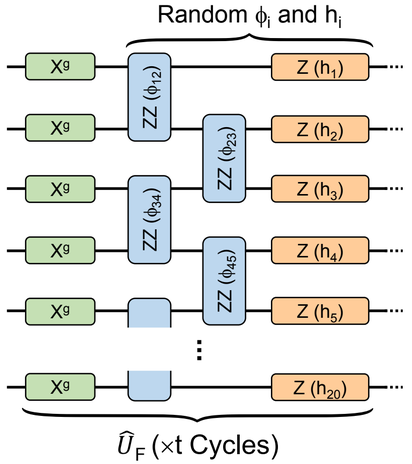
Choi…VK…Bloch, Gross, Science (2016)

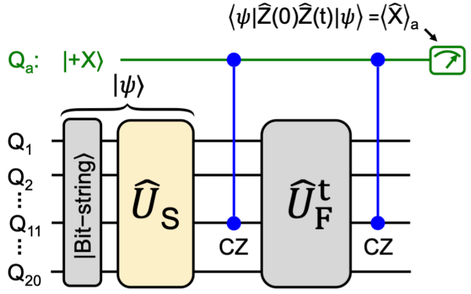
Anderson 1958; Basko Aleiner Altshuler 2006; Oganesyan Huse 2007 + …

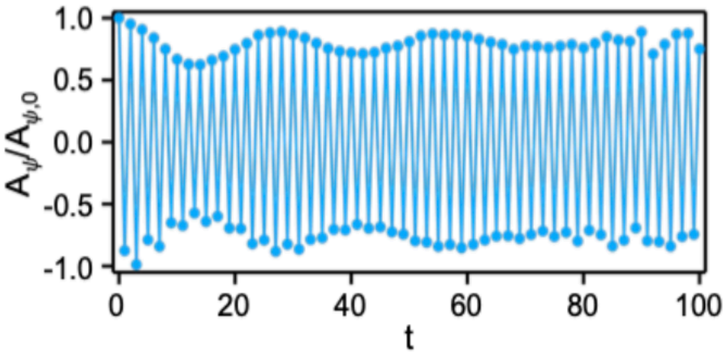


Time-Crystalline
eigenstate order
(spatiotemporal)

VK. Lazarides, Moessner, Sondhi (2015)
Else Bauer Nayak (2016)+ …







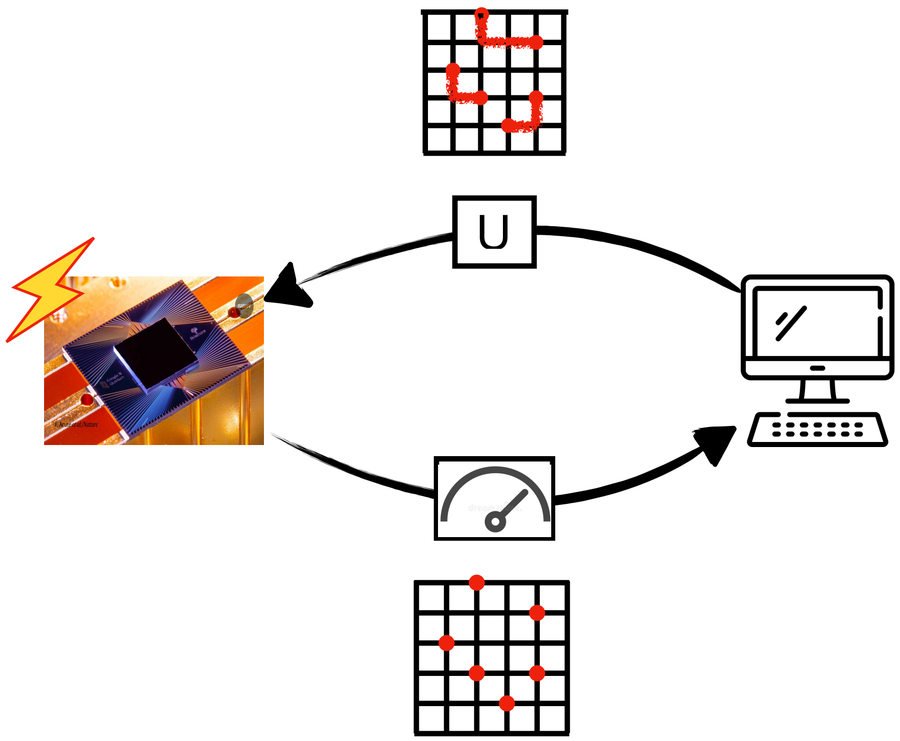
Mi, Ippoliti…VK, Roushan, Nature (2022)

II. Monitored Dynamics: Controlled Measurements

Active error correction

Noise adds entropy

Destroys coherence

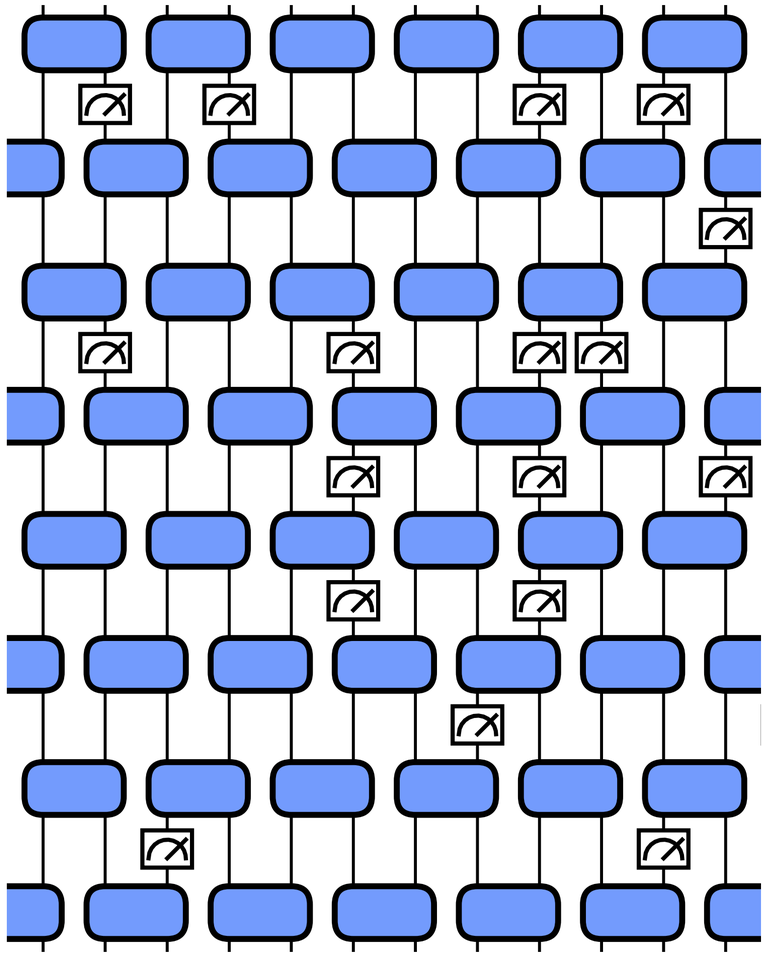


Measurements + feedback remove entropy

Restores coherence

Information protection via information processing

Monitored Dynamics: Controlled Measurements



Measurement *as a **part*** of many-body dynamics

Measurements can have a dramatic effect on the state being measured: can **create, destroy and restructure** quantum correlations.

Get new **nonequilibrium phases** defined by **structure of quantum information in spacetime**

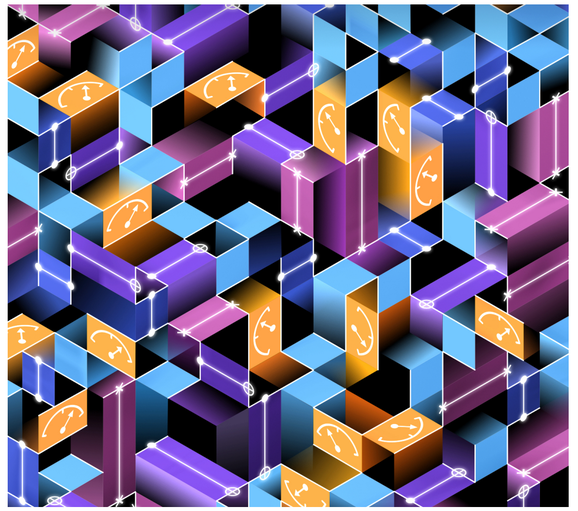
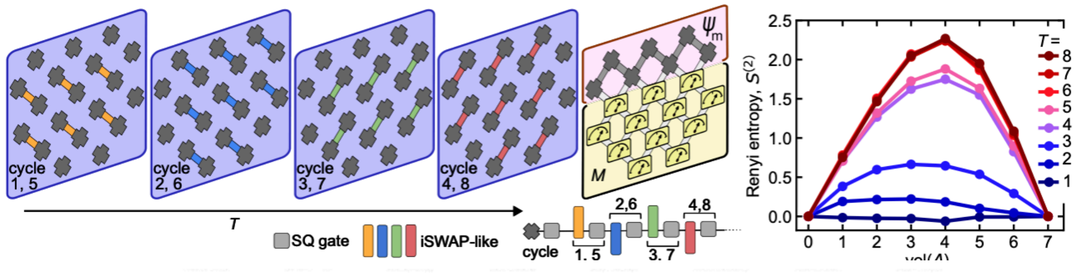


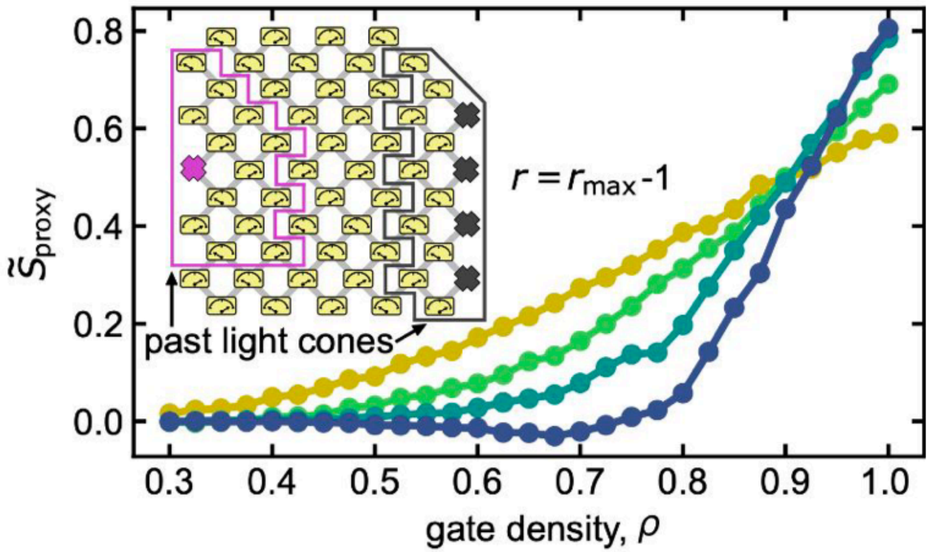
Image: Google Quantum AI

Monitored Dynamics: Controlled Measurements

Measurement Induced Phase Transition

in individual quantum trajectories





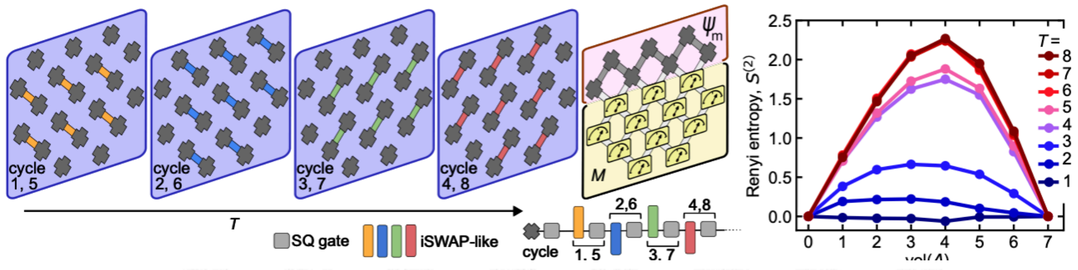
Hoke, Ippoliti…VK, Roushan, Nature (2023)

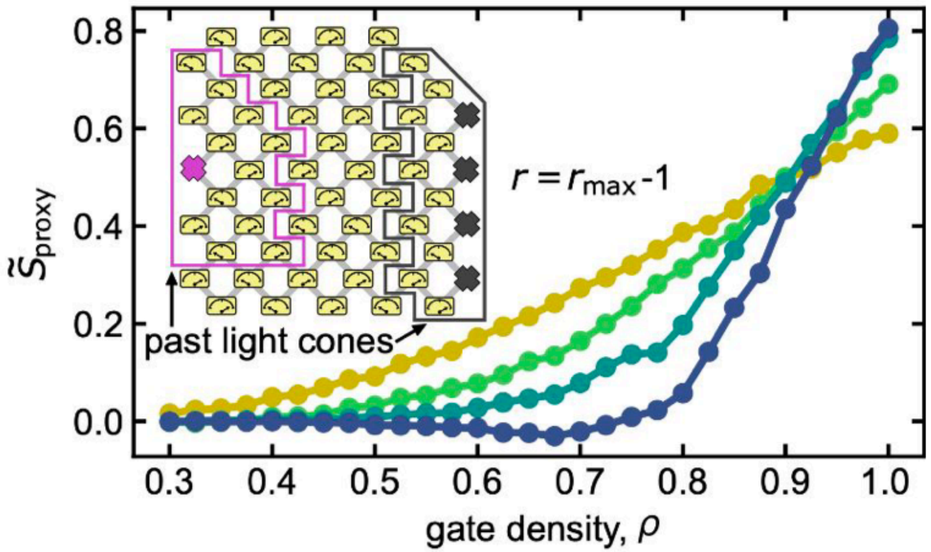
Li Chen Fisher (2018) Skinner Ruhman Nahum (2018)

Monitored Dynamics: Controlled Measurements

Measurement Induced Phase Transition

in individual quantum trajectories





Hoke, Ippoliti…VK, Roushan, Nature (2023)

Li Chen Fisher (2018) Skinner Ruhman Nahum (2018)

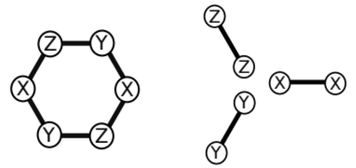
Measurement-only Dynamics

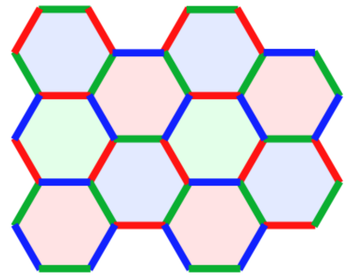
Ippoliti…VK PRX 2021

Lavasani, Alvirad, Barkeshli Nature Physics 2021

Sang Hsieh PRR 2021

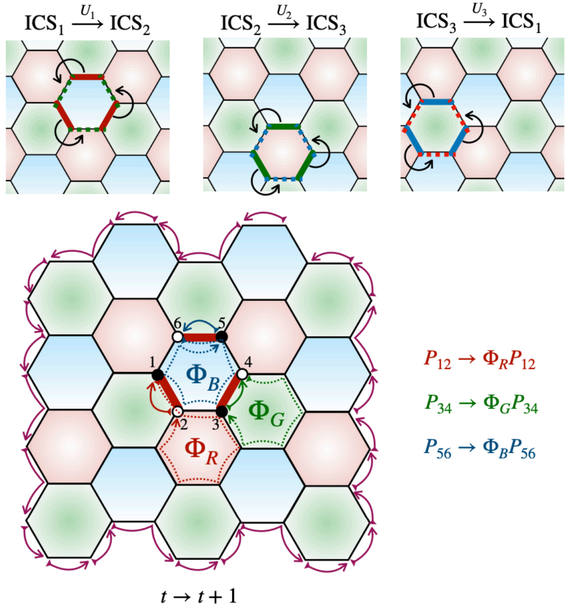
Hastings-Haah Floquet Code (2021)





- Periodic sequence of **local measurements**
- **Dynamically generated error correcting code**
- Code and logical operators transform periodically in time
- $e \rightleftarrows m$ automorphism after every period
  - "Topological" time-crystal

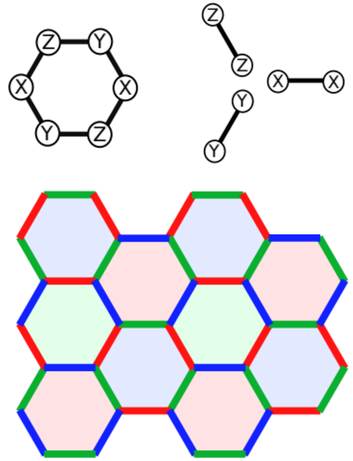
Unitary MBL Floquet Topological Order ↔ Measurement-only Floquet Code



Sullivan Wen Potter (2023)

Aasen Haah Li Wong (2023)

Roberts Vijay Dua (2023)



MBL Floquet Topological Phase
(Po et al 2017)

Measurement-only Floquet Code
(Hastings Haah 2021)

Controllable Geometry and Interactions

A recent theoretical breakthrough: good quantum LDPC codes

LDPC: every (qu)bit talks to only a finite number of (qu)bits

low density parity check

$[n, k, d]$

physical bits

code distance
(smallest undetectable error)

encoded (logical) bits

Good code:

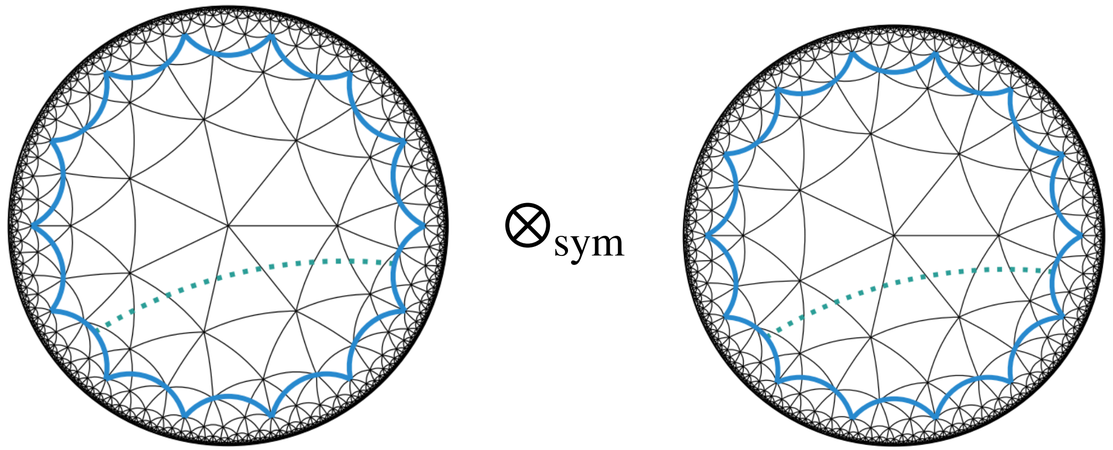
$k \propto n$ ← Low overhead!

$d \propto n$ ← Very robust!

Breuckmann Eberhardt 2021

Pantaleev, Kalachev 2021

Leverrier, Zemor 2022



Requires **expander graph**

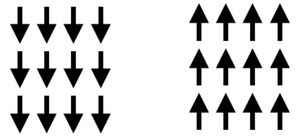
boundary is proportional to volume

The Physics of LDPC Codes

Rakovszky VK (2023)
Rakovszky VK (2024)
Placke Rakovszky Sommers Breuckmann VK (in progress)

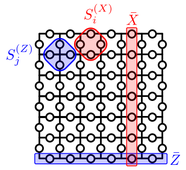
Error Correcting Codes ⟷ **Ordered Phases of Matter**

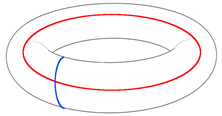
Classical Code (Repetition)



Symmetry Breaking

Quantum Code (Toric code)





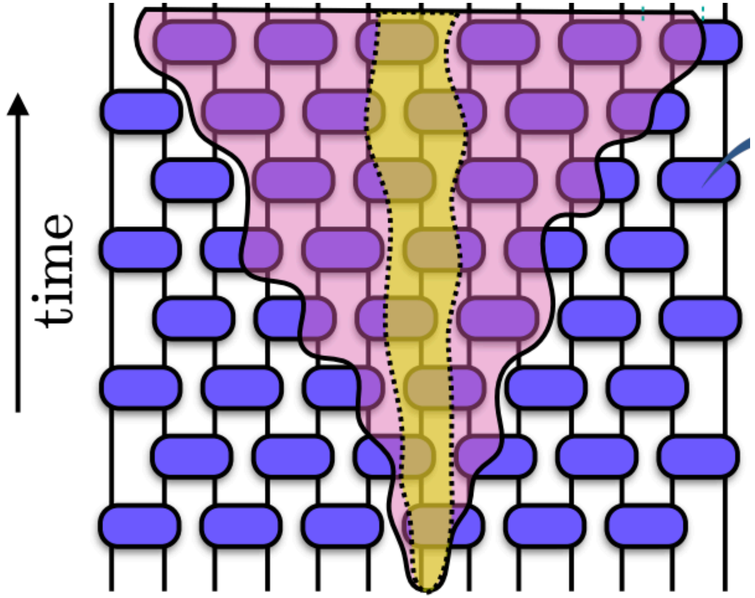
Topological Order

LDPC Codes

Novel gauge theories
and spin glasses

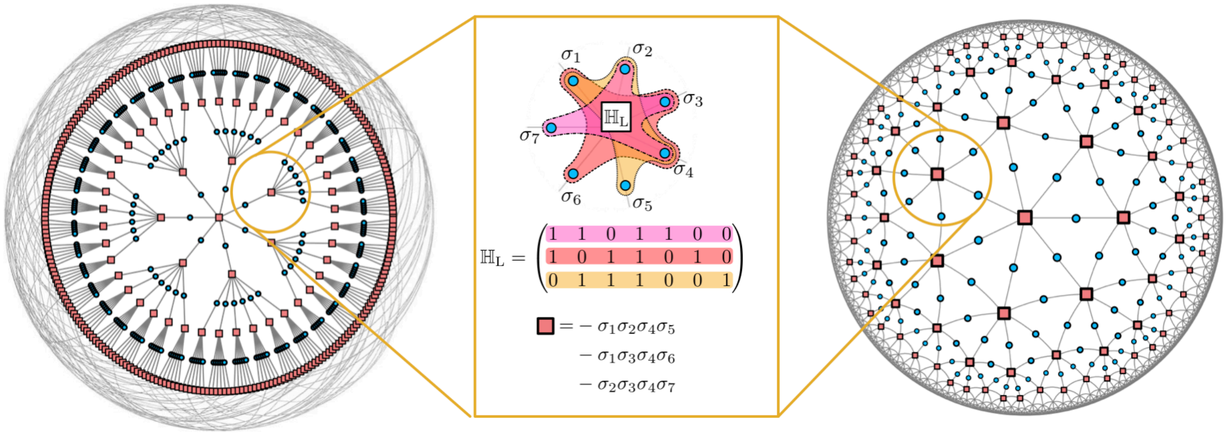
QUANTUM NETWORK

*A system of many strongly and **controllably interacting** quantum elements organized by the **structure and flow of quantum information***



Fisher, Khemani, Nahum, Vijay ARCMP 2023

Dynamics: flow of quantum information in spacetime



“good LDPC codes”

Engineered interactions and **geometry**