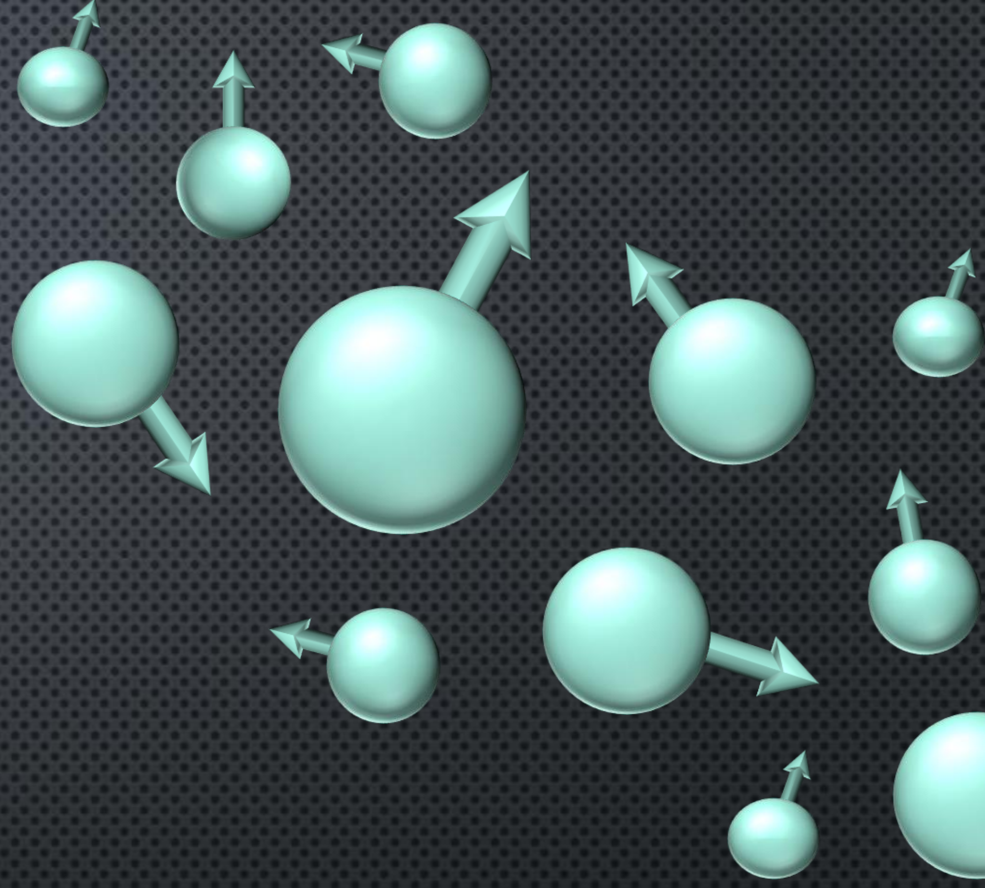
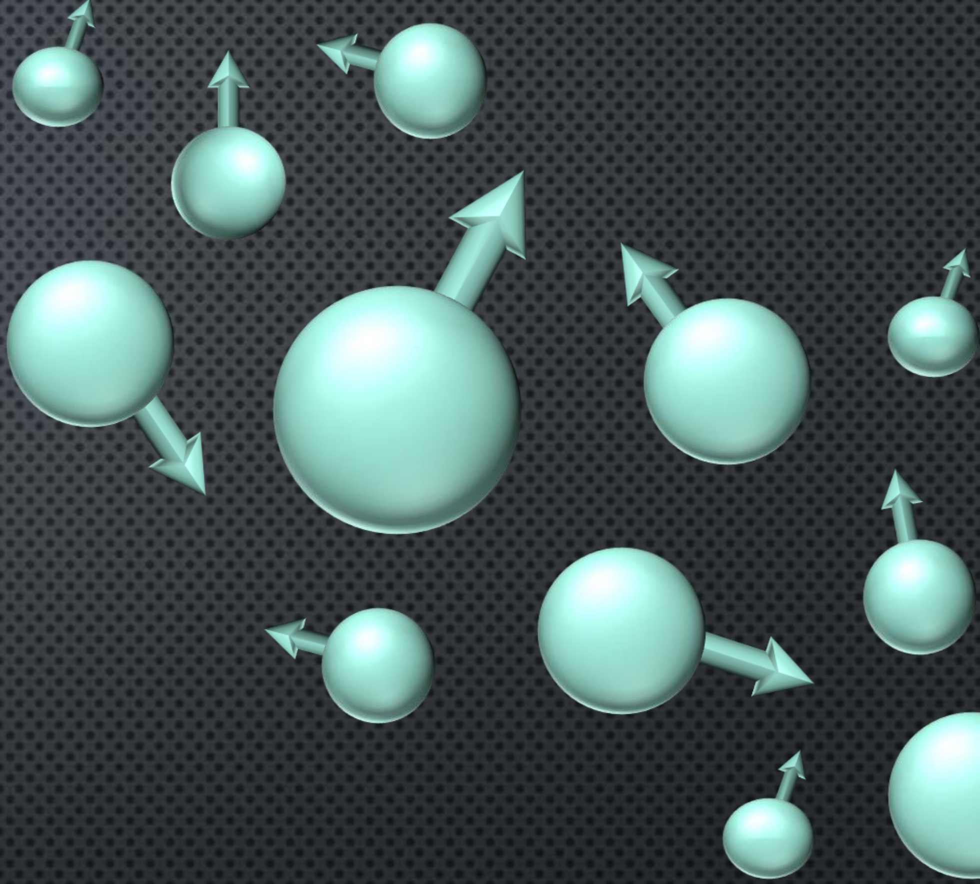
Calculating Nature Naturally



Theory Seminar at NSCL/FRIB
East Lansing, Michigan. October 20^{th} 2020

Natalie Klco

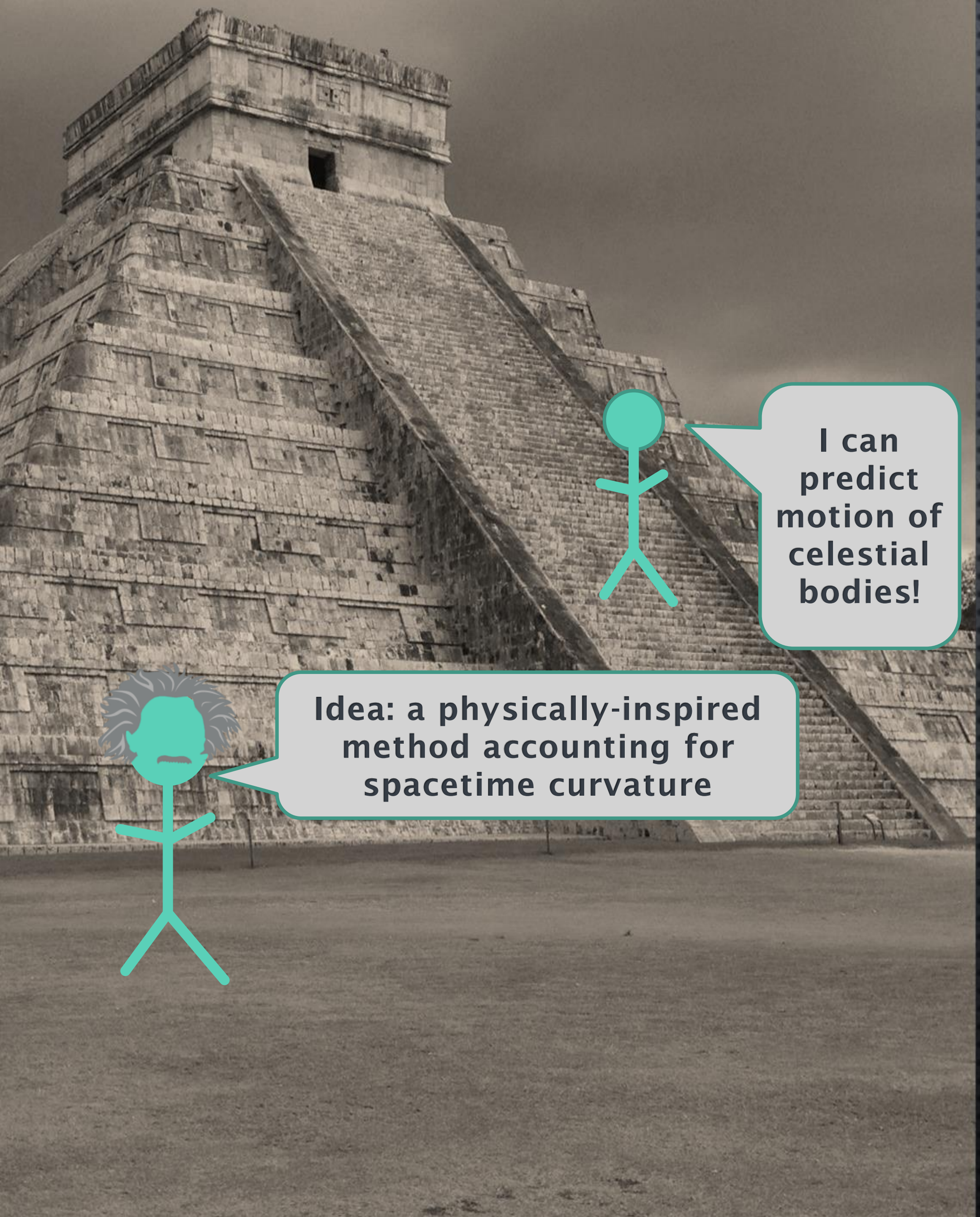
Calculating Nature Naturally

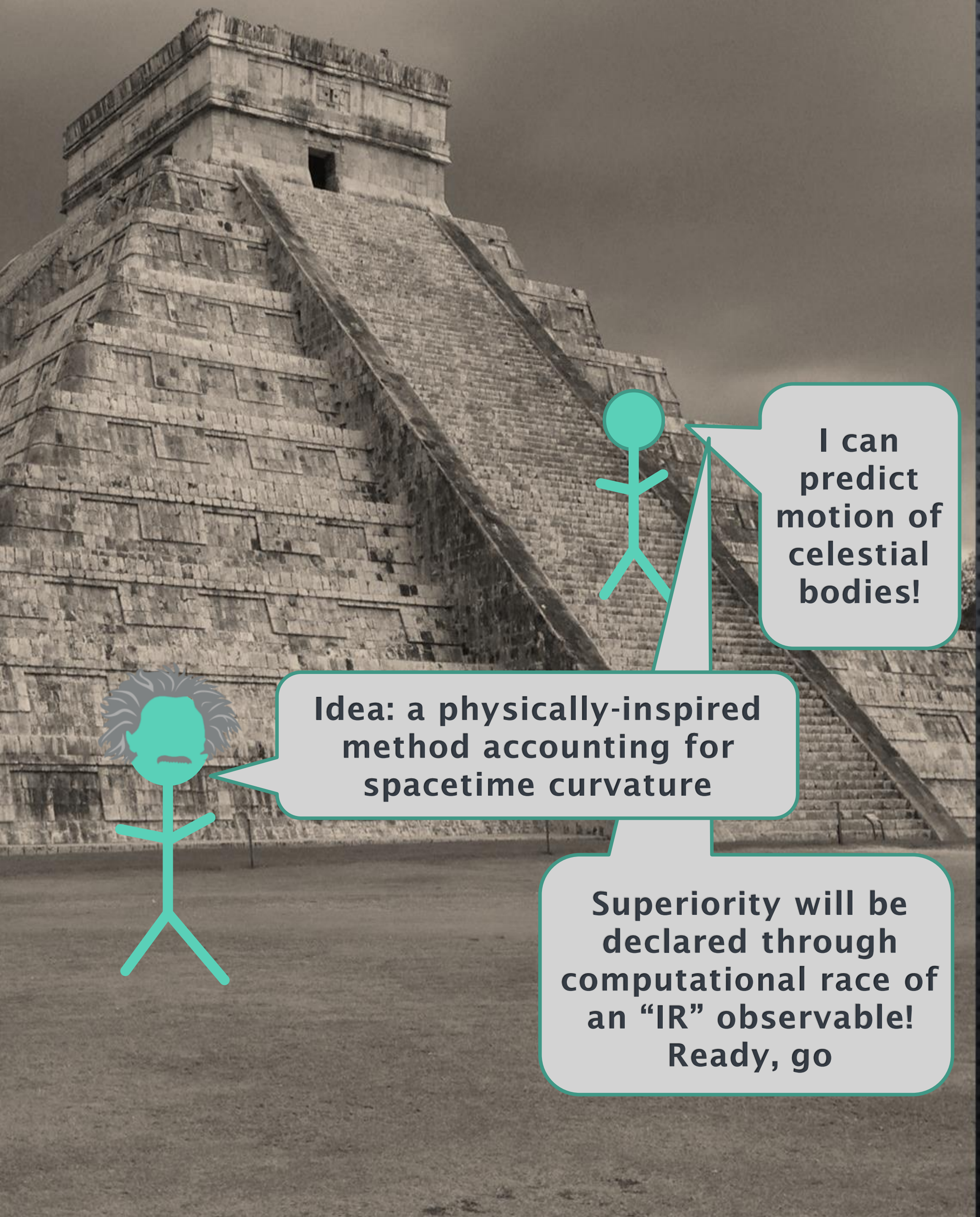


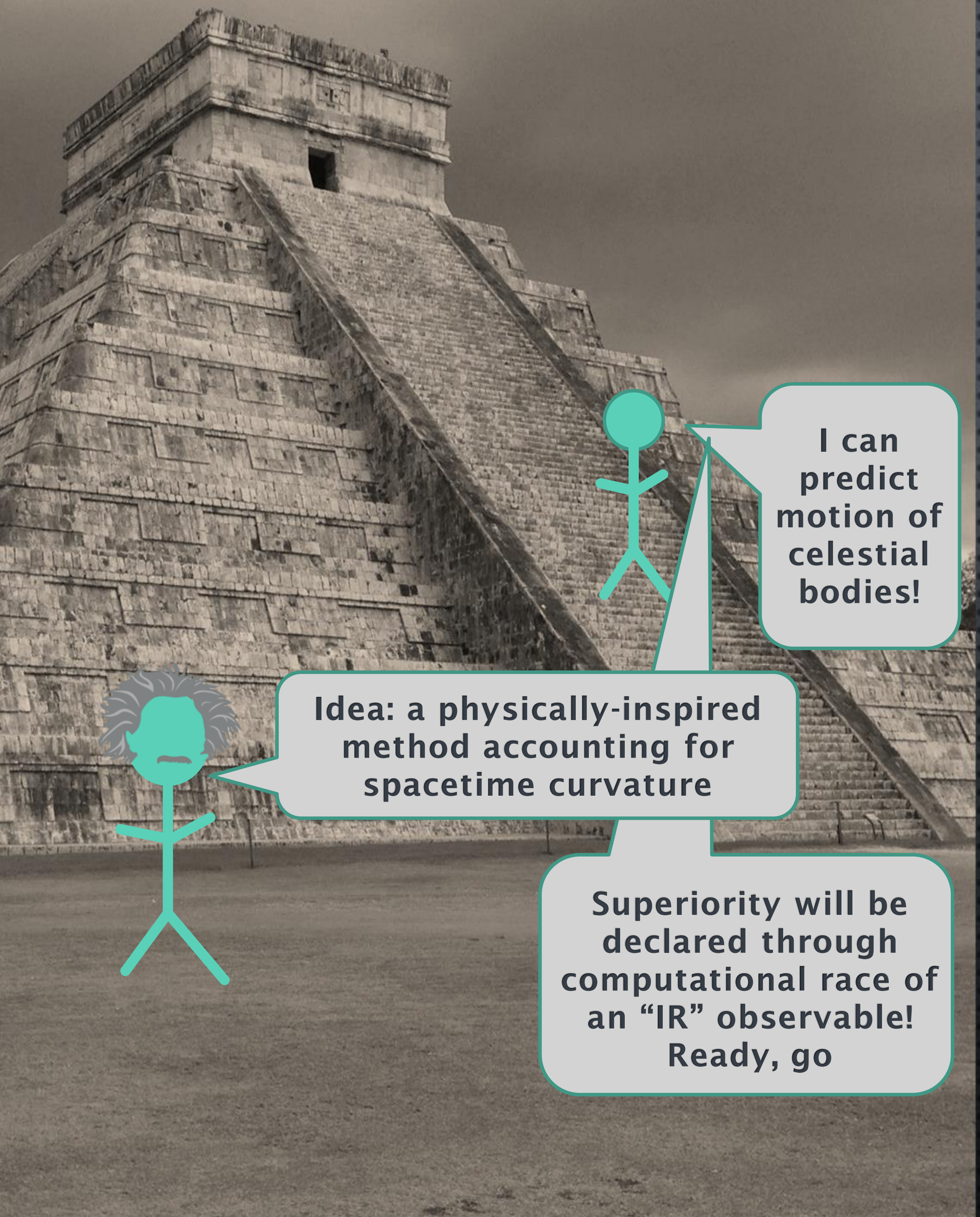
Leveraging Quantum Degrees of Freedom to Calculate Quantum Dynamics

An Entanglement Perspective


I can predict motion of celestial bodies!


I can predict motion of celestial bodies!
Idea: a physically-inspired method accounting for spacetime curvature

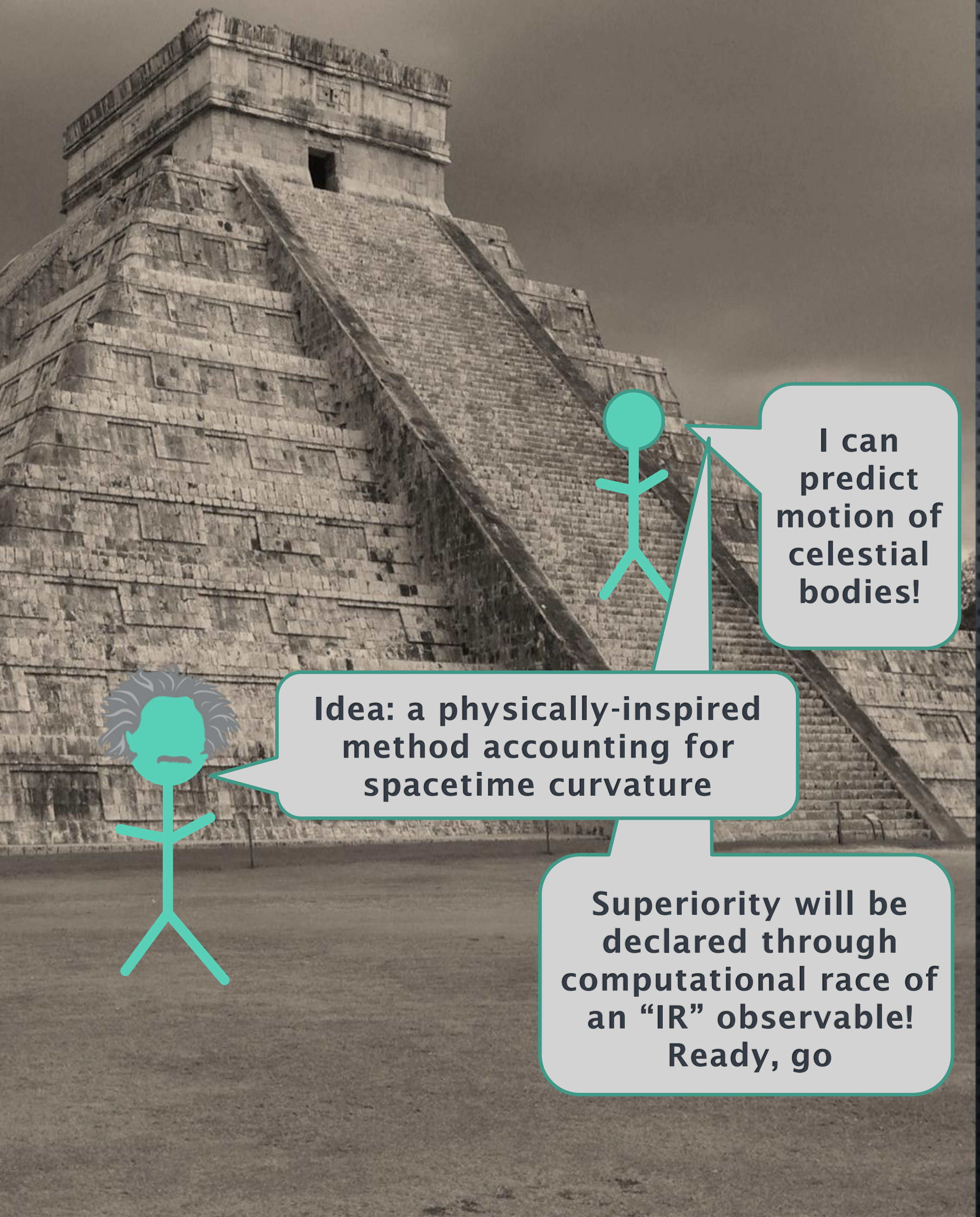

I can predict motion of celestial bodies!
Idea: a physically-inspired method accounting for spacetime curvature
Superiority will be declared through computational race of an “IR” observable! Ready, go



Calculating Nature Naturally

The ideas underlying a computational framework affect the ease with which its many units of nature can be choreographed in performance

Opportunity to deeply align our calculations with Nature

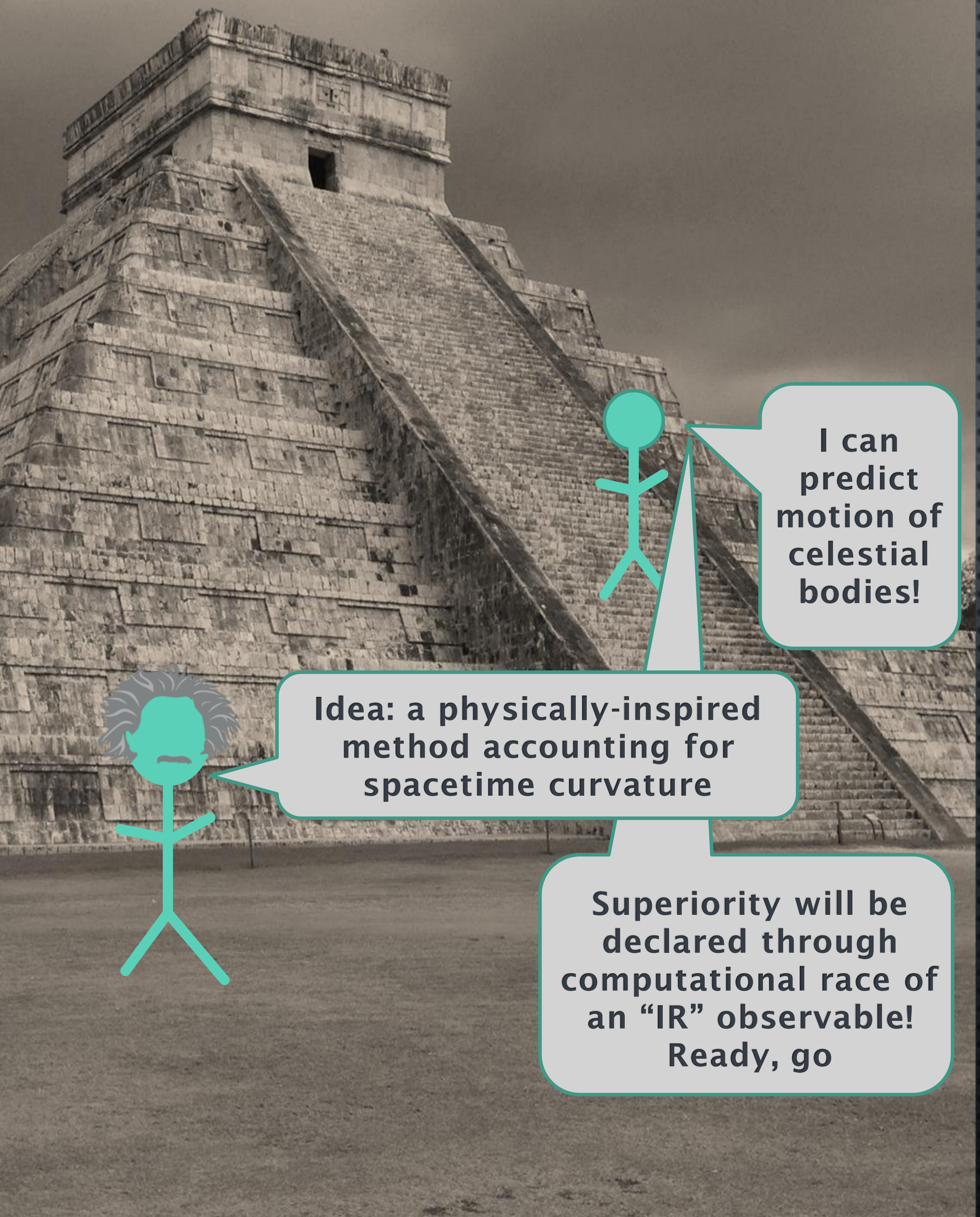


Calculating Nature Naturally

The ideas underlying a computational framework affect the ease with which its many units of nature can be choreographed in performance

Opportunity to deeply align our calculations with Nature

Historically rare for a dramatic restructuring of a computational framework to be embraced before scientifically-relevant supremacy is proven.



Calculating Nature Naturally

The ideas underlying a computational framework affect the ease with which its many units of nature can be choreographed in performance

Opportunity to deeply align our calculations with Nature

Historically rare for a dramatic restructuring of a computational framework to be embraced before scientifically-relevant supremacy is proven.

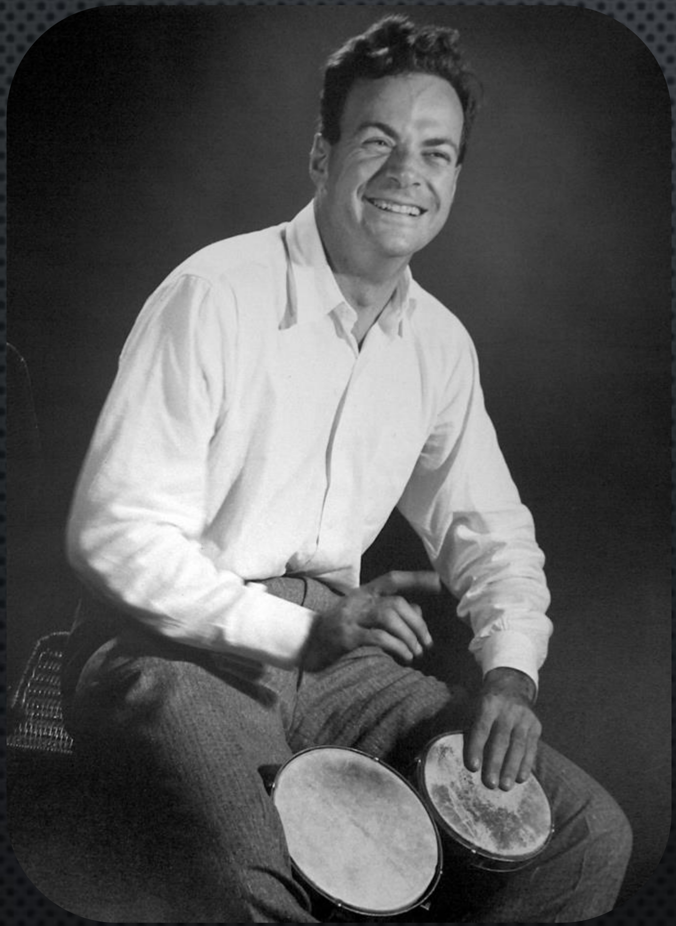
~~Whim~~ Inevitable Progression of Research:

- ~100 years: Clear theory understanding of interactions suffering prohibitive costs to calculate emergent collective phenomena
- ~100 years: Overwhelming experimental evidence for distinct physical phenomena (entanglement)
- ~25 years: Strong theoretical evidence of complexity separation
- ~40 years: Shared vision developed across disciplines. Ability to see further.

Our Quantum Universe

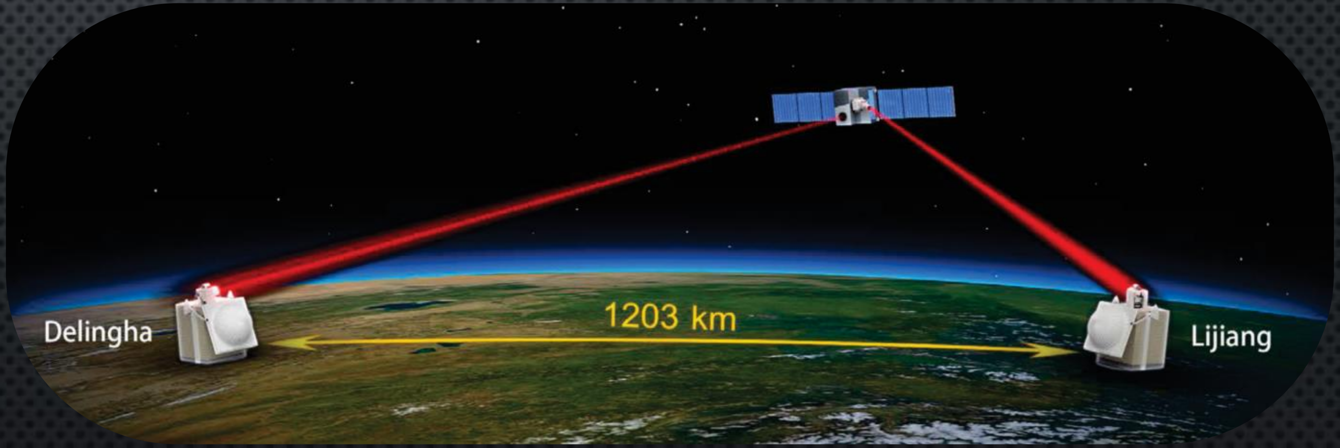
There exist correlations in nature that cannot be imitated by deterministic, local classical computations

(1935): EPR paradox
(1964): Bell's experiment
(1982): Aspect-Grainger experimental realization



Satellite-based entanglement distribution over 1200 kilometers

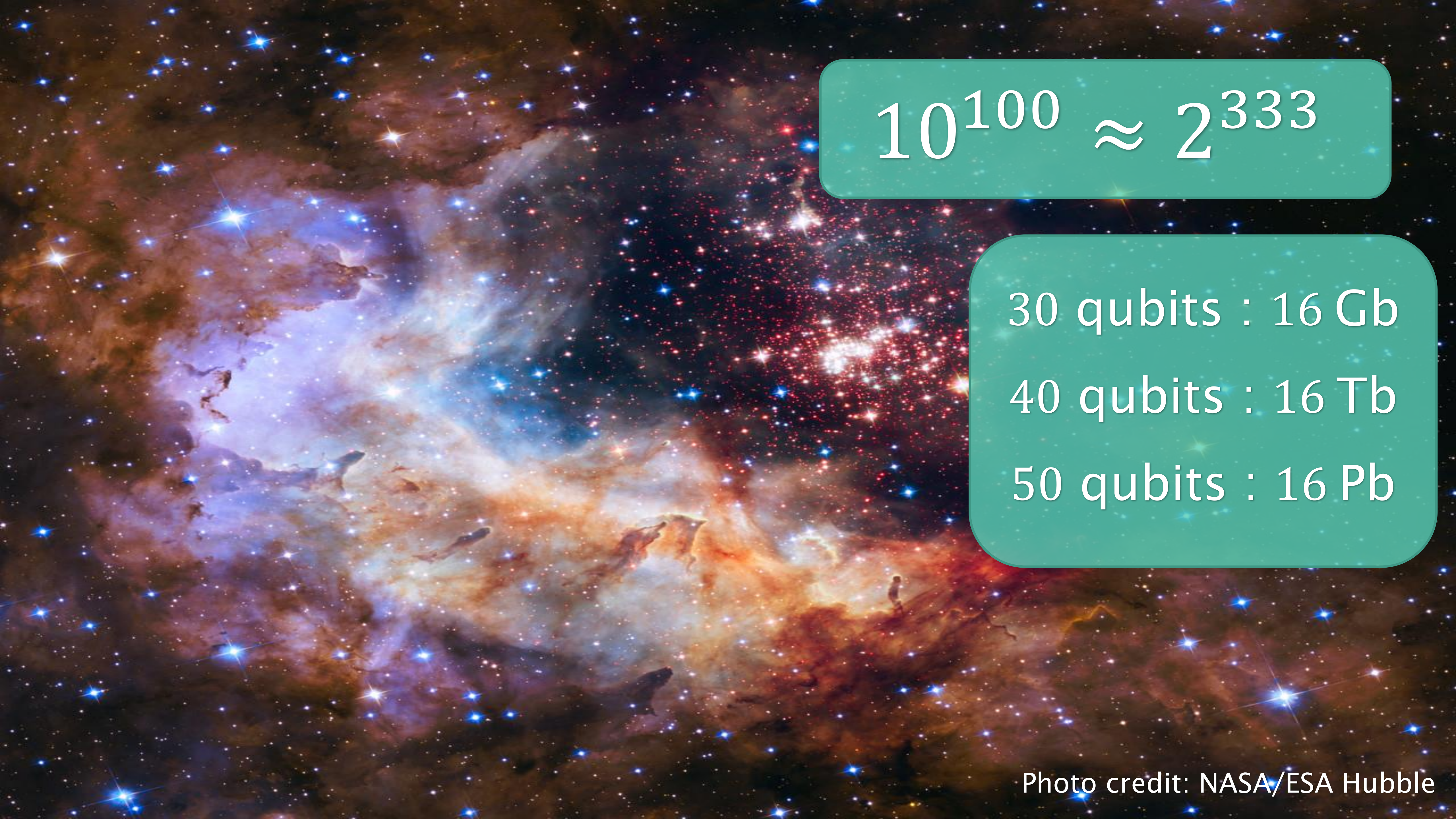
Yin *et al.*, *Science* **356**, 1140–1144 (2017) 16 June 2017



"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." --Feynman (1980)

$$10^{100} \approx 2^{333}$$

Photo credit: NASA/ESA Hubble



$10^{100} \approx 2^{333}$

30 qubits : 16 Gb

40 qubits : 16 Tb

50 qubits : 16 Pb

Photo credit: NASA/ESA Hubble

Entanglement

QI stored non-locally
in **correlations**
between pages

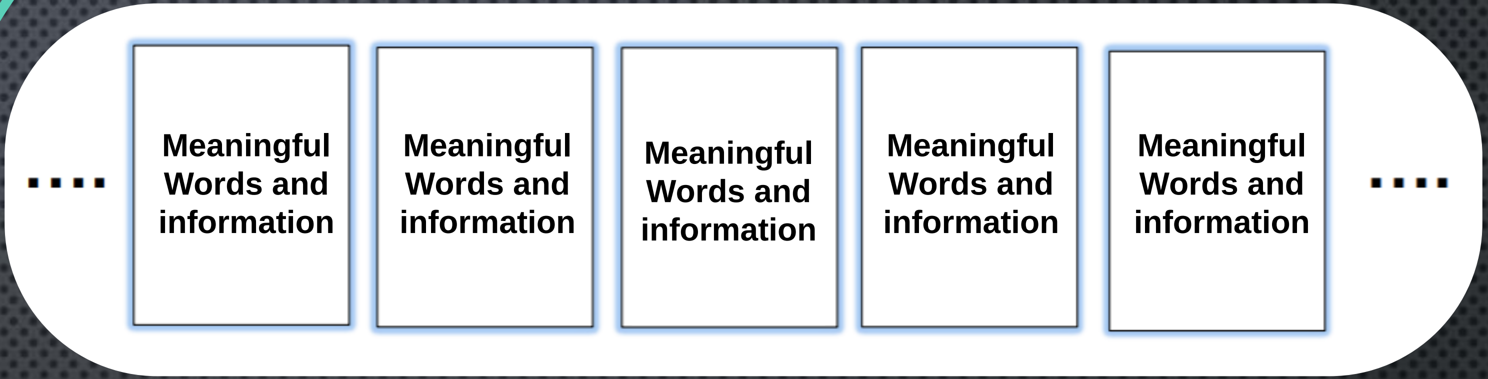
Entropy

$$S \cong N - 2^{-(N+1)}$$

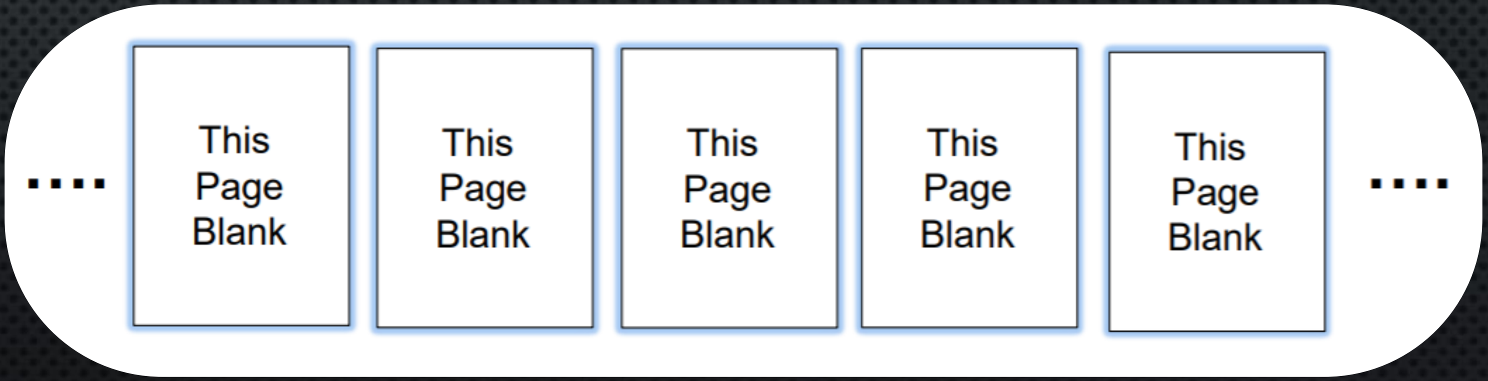
subsystem information
decreases exponentially

Page (1993)

Classical Book



Preskill's Quantum Book



Intellectual Phase Transition ~1995-1998

(1995) DiVincenzo:

- Two-bit gates are universal for quantum computation
- e.g., No fundamental 3-body operators necessary

(1995) Solovay-Kitaev Theorem:

- Efficient generating gate set for digital QC

(1995) Shor Quantum Error Correction Code:

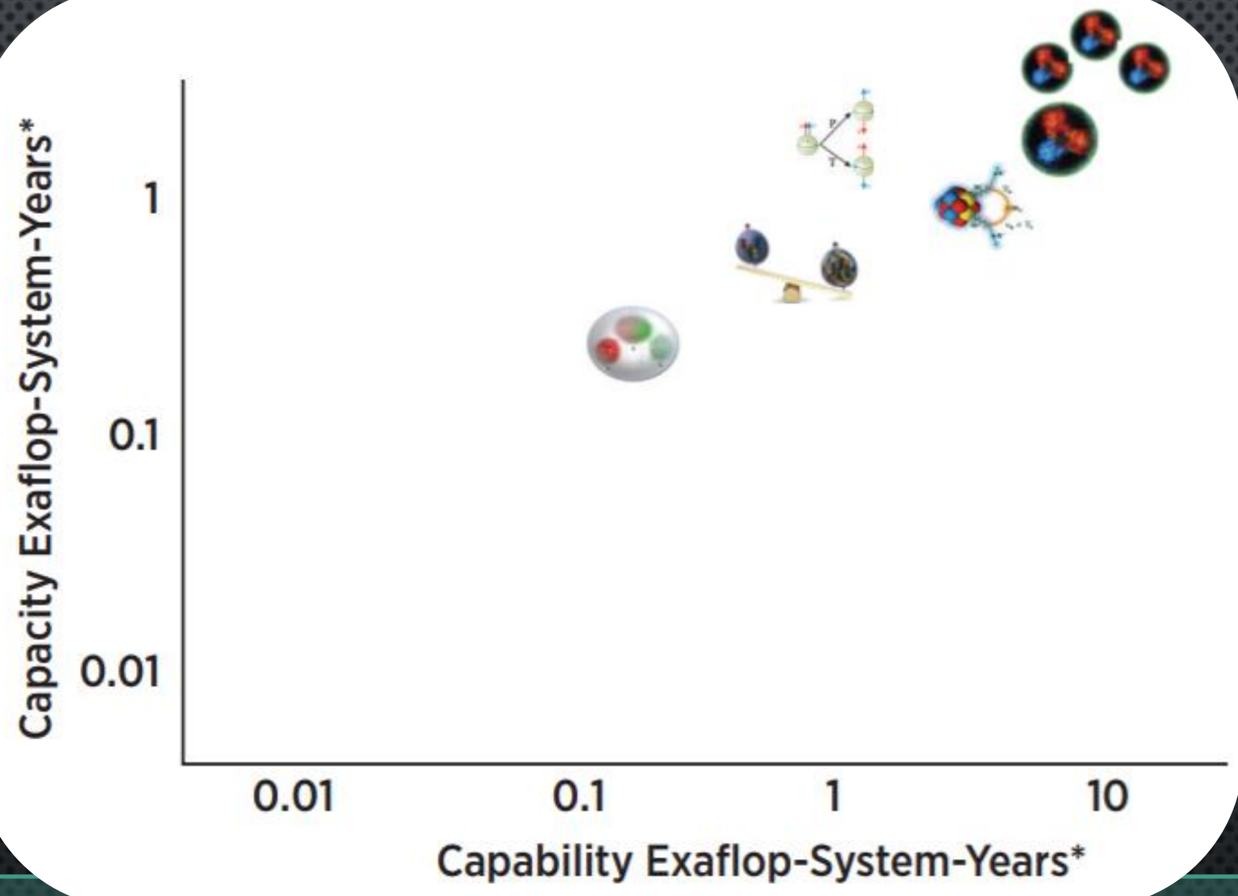
- Shor, Steane, Calderbank, Bennett, DiVincenzo, Smolin, Wootters…
- Quantum states can be protected from continuous errors!

(1996) Threshold Theorem:

- Knill-Laflamme, Gottesman, Aharonov, Ben-Or, Kitaev
- Below threshold, arbitrarily long QC possible

What should we do with it?

2016 estimates for 2025 computing requirements



Exotic decays — Gluonic structure — EDM — 0νββ

Precision g_A, and charge radii and electromagnetic form factors — Three-nucleon forces

* Exaflop-system-year refers to the total amount of computation produced by an exascale computer in 1 year.

DOE EXASCALE REQUIREMENTS REVIEW — NP/ASCR

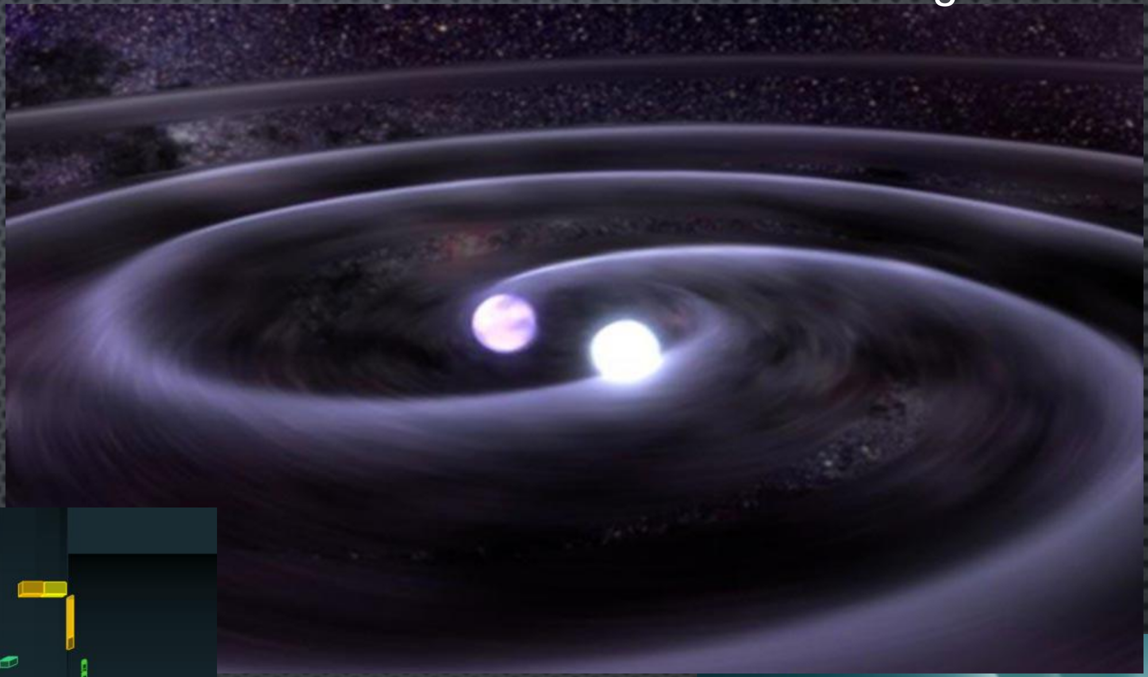
Neutrino Transport

Resonance Properties

Non-Equilibrium Dynamics

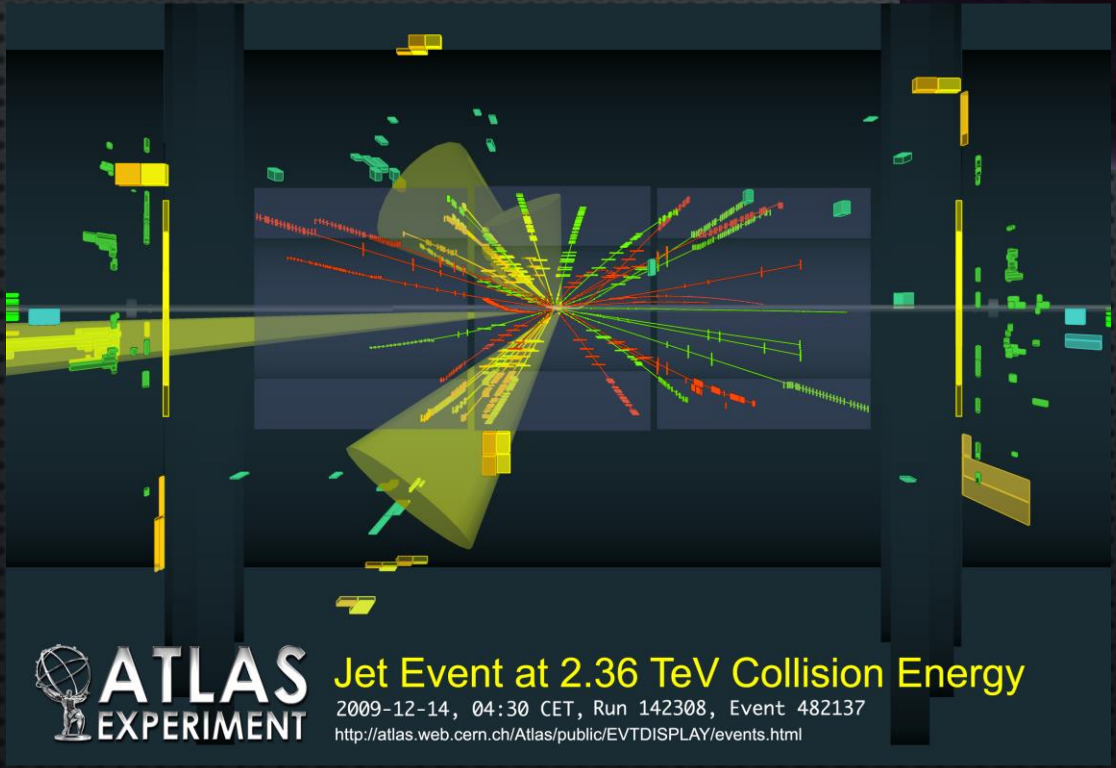
Scattering Amplitudes/Phase Shifts

NASA animation of Neutron star merger



Finite Density Systems

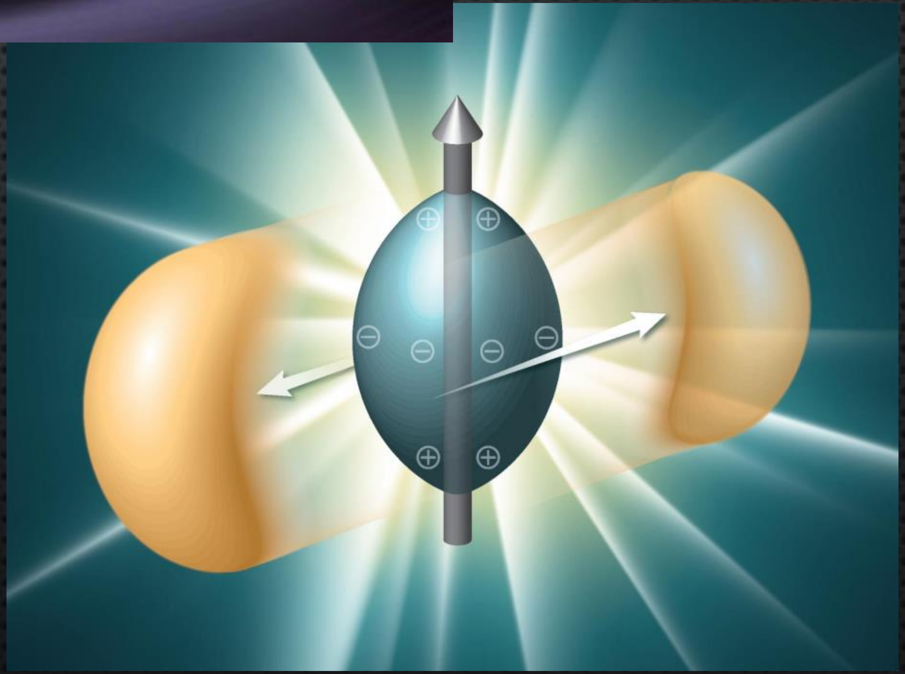
Fragmentation Functions



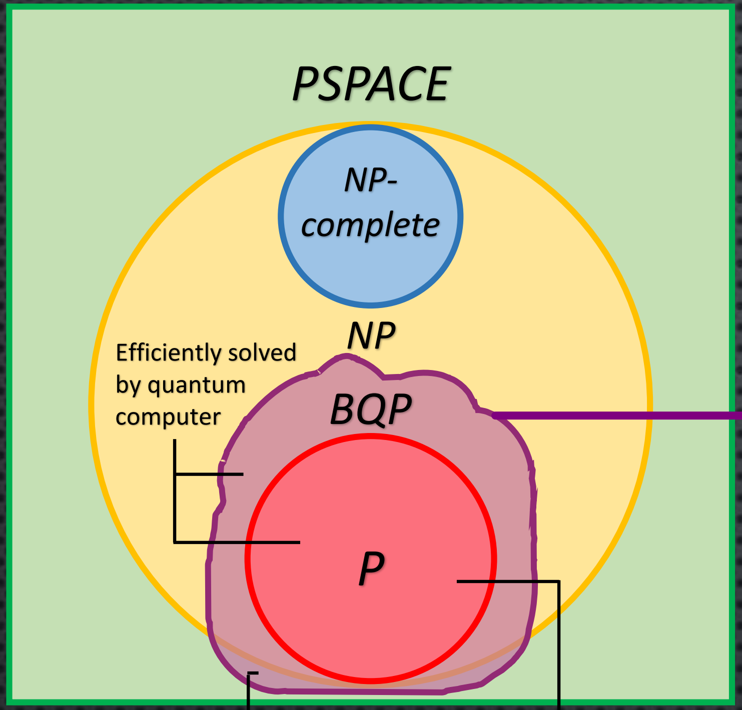
Atlas (2011)

Real-Time Evolution of Quantum systems

Phys. Rev. Lett. 114, 252302 (2015)



Aaronson (Sci. Am.)



Role of Quantum Fields

computation ~ quantum field

nature ~ quantum field

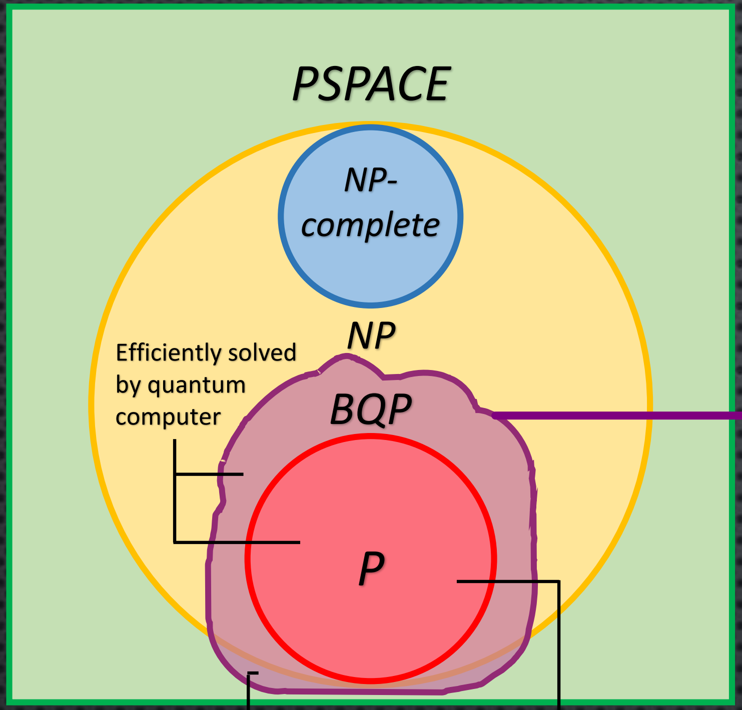
Vac-vac $\lambda\phi^4$+ classical sources (Jordan, Krovi, Lee, Preskill) 2018

Forrelation oracle separation (Raz, Tal)

Efficiently solved by classical computer

- Q Sim. efficient for local Hamiltonians (Feynman, Lloyd)
- Scattering efficient--massive $\lambda\phi^4$, Gross Neveu--precision, energy, particle #, coupling strength (Jordan, Lee, Preskill)
- BQP Hard: Vacuum-to-Vacuum in massive $\lambda\phi^4$ with classical sources. Map all of BQP. (Jordan, Krovi, Lee, Preskill)
- BQP Complete: universal for QC (Jordan, Krovi, Lee, Preskill)

Aaronson (Sci. Am.)



Vac-vac $\lambda\phi^4$+ classical sources
(Jordan, Krovi, Lee, Preskill) 2018

Forrelation oracle separation (Raz, Tal)

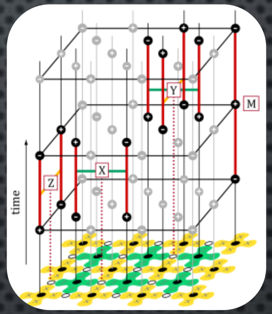
Efficiently solved by classical computer

Role of Quantum Fields

computation
~
quantum field

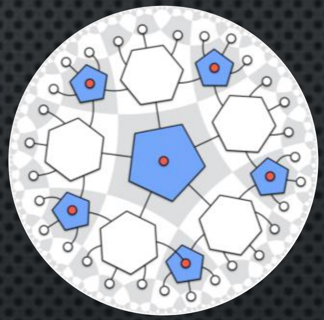
nature
~
quantum field

qubit array
~
quantum field

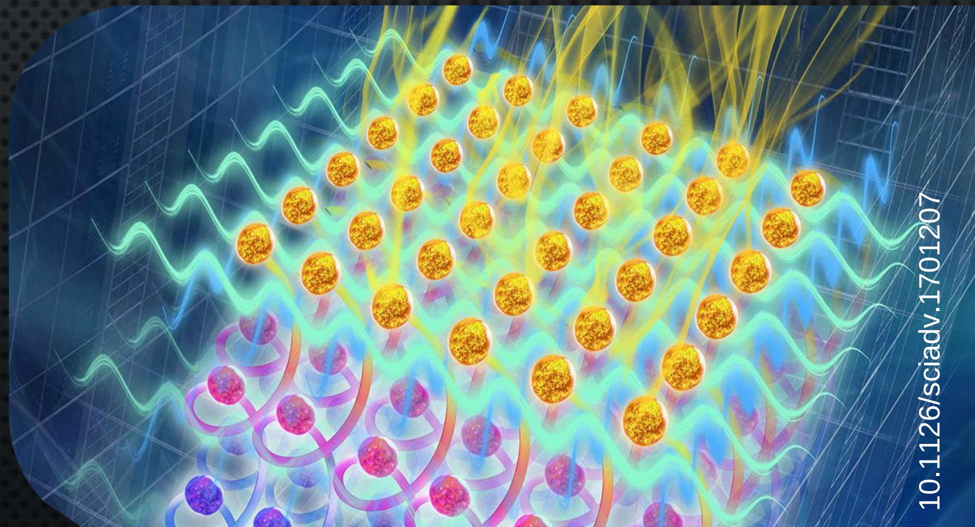


Surface Codes
Kitaev (1997)

Holographic Codes
Pastawski, Yoshida, Harlow, Preskill (2015)



Analog Simulators



- Q Sim. efficient for local Hamiltonians (Feynman, Lloyd)
- Scattering efficient--massive $\lambda\phi^4$, Gross Neveu--precision, energy, particle #, coupling strength (Jordan, Lee, Preskill)
- BQP Hard: Vacuum-to-Vacuum in massive $\lambda\phi^4$ with classical sources. Map all of BQP. (Jordan, Krovi, Lee, Preskill)
- BQP Complete: universal for QC (Jordan, Krovi, Lee, Preskill)

Research Program:

Simulation on NISQ Devices

Inform Beyond-NISQ Specifications for Scientific Application

Flexibility with Hardware Availability

Theory and Experiment Codesign

Grounded in Reality

Translation to Qubit DOF

Develop Versatility in High-Dimensional Optimization

Natural Design of Hilbert Space

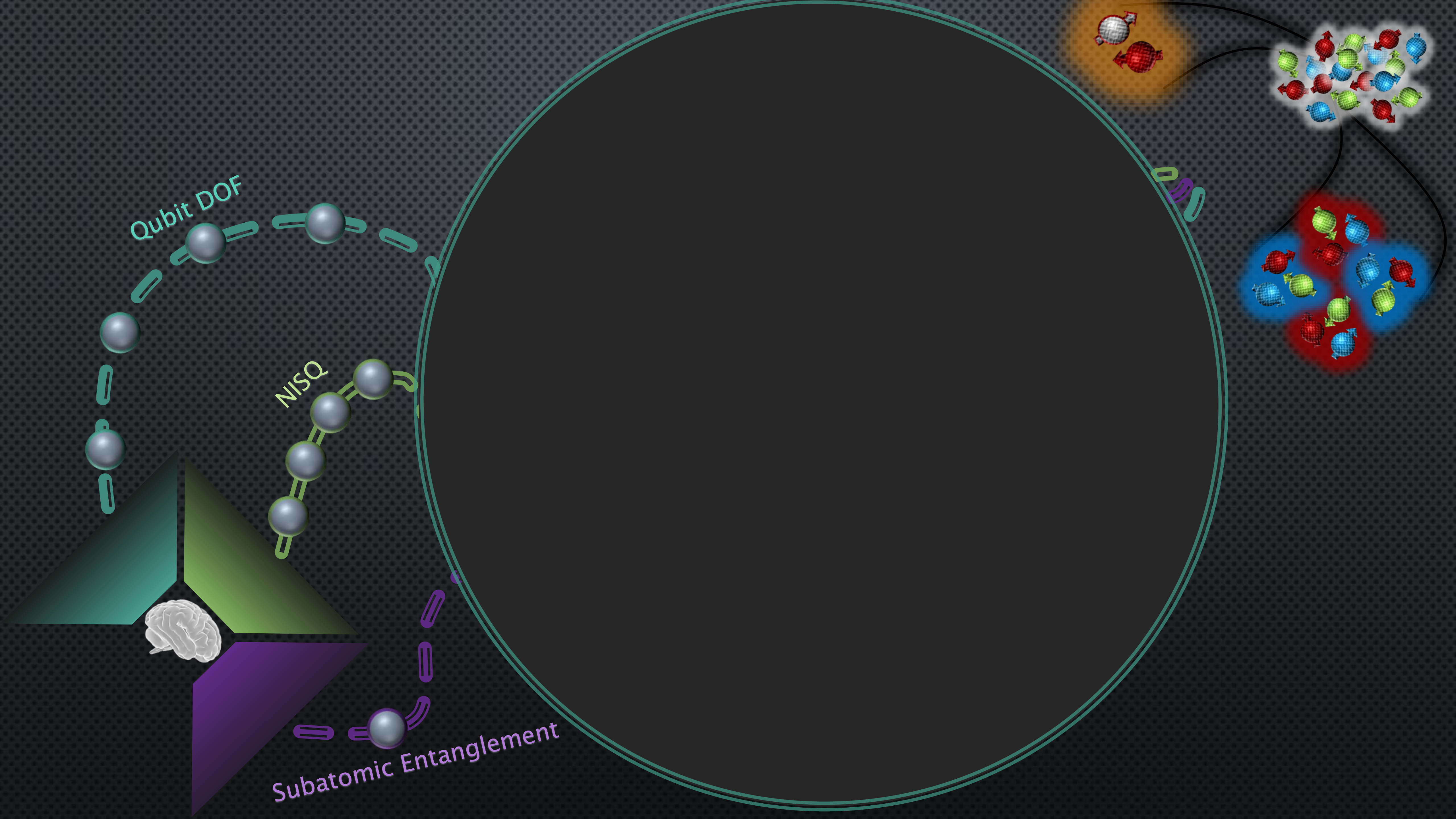
Isolating Physical Subspaces

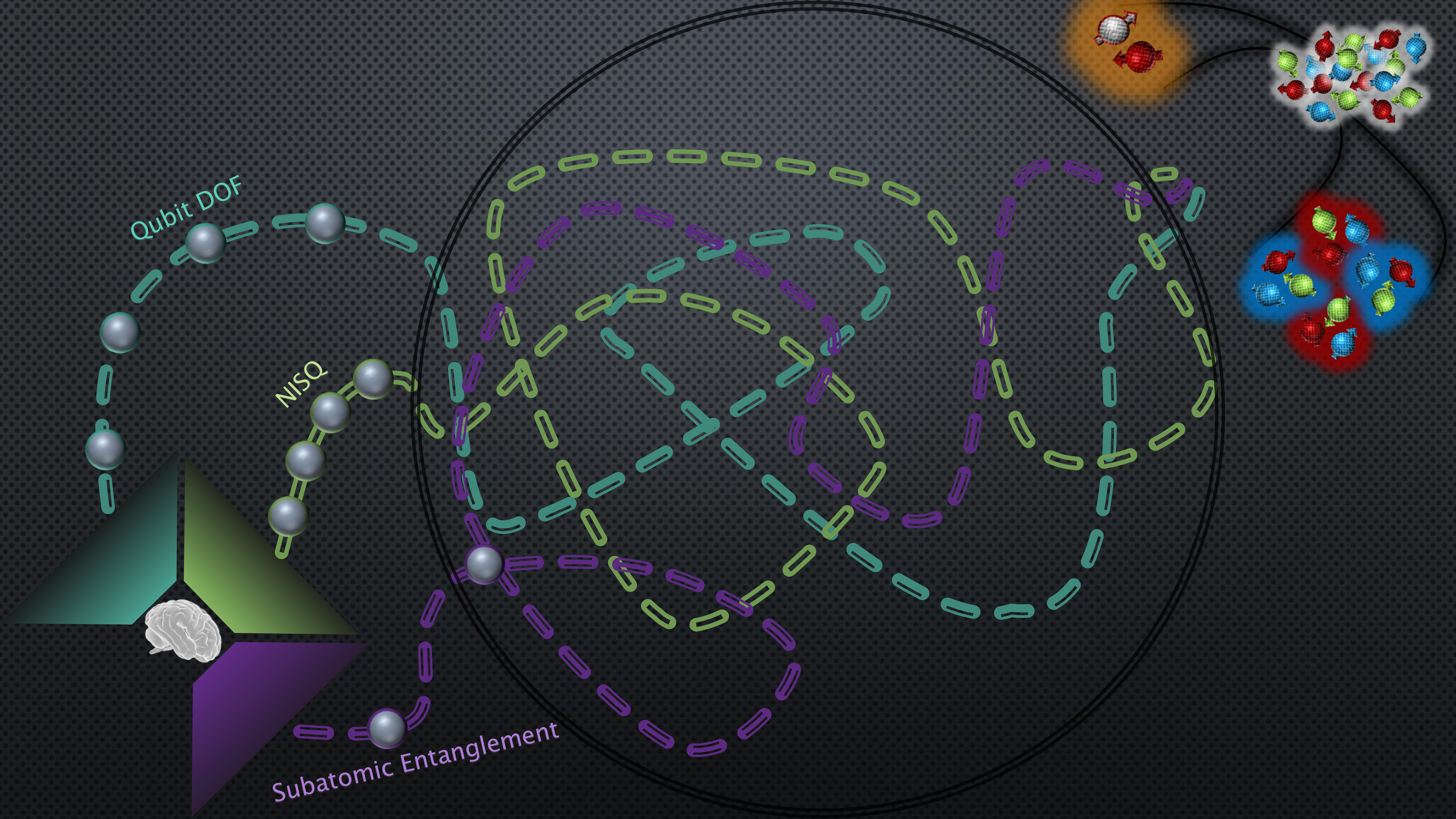
Entanglement in Subatomic Physics

Entanglement Beyond Computation

Role of Quantum Correlations in Field Theory

Entanglement as a Function of Scale


Qubit DOF
NISQ
Subatomic Entanglement


Qubit DOF
NISQ
Subatomic Entanglement

SciPost Phys. 3, 036 (2017)

Maximal entanglement in high energy physics

Alba Cervera-Lierta[1], José I. Latorre[1,2], Juan Rojo[3] and Luca Rottoli[4]

PHYSICAL REVIEW D **95,** 114008 (2017)

Deep inelastic scattering as a probe of entanglement

Dmitri E. Kharzeev[1,2,*] and Eugene M. Levin[3,4,†]

Thermal radiation and entanglement in proton-proton collisions at energies available at the CERN Large Hadron Collider

O. K. Baker and D. E. Kharzeev

Phys. Rev. D **98**, 054007 – Published 10 September 2018

Chiral symmetry breaking, entanglement, and the nucleon spin decomposition

Silas R. Beane[1] and Peter Ehlers[1]   arXiv:1905.03295v1

SciPost | SciPost Phys. 3, 036 (2017)

Maximal entanglement in high energy physics

Alba Cervera-Lierta[1], José I. Latorre[1,2], Juan Rojo[3] and Luca Rottoli[4]

PHYSICAL REVIEW D **95,** 114008 (2017)

Deep inelastic scattering as a probe of entanglement

Dmitri E. Kharzeev[1,2,*] and Eugene M. Levin[3,4,†]

Chiral symmetry breaking, entanglement, and the nucleon spin decomposition

Silas R. Beane[1] and Peter Ehlers[1] arXiv:1905.03295v1

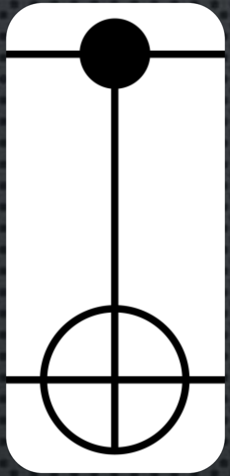
Role of entanglement at low energies?

Entanglement Suppression and Emergent Symmetries of Strong Interactions

Silas R. Beane,[1] David B. Kaplan,[2] Natalie Klco,[1,2] and Martin J. Savage[2]

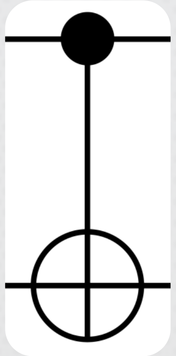
Capability of S matrix to entangle?

CNOT as entangling operator



CNOT + (1-qubit ops) sufficient for universal QC

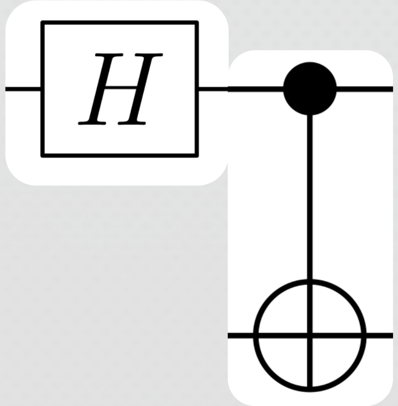
Basis State →



$$\begin{pmatrix} 1 & & & \\ & 1 & & \\ & & & 1 \\ & & 1 & \end{pmatrix}$$

→ Basis State

Basis State →

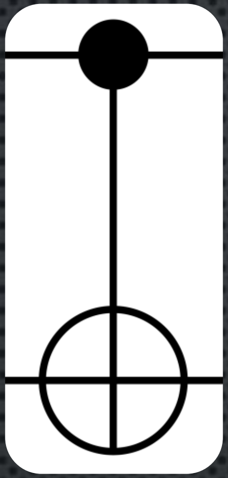


$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & & 1 & \\ & 1 & & 1 \\ & 1 & & -1 \\ 1 & & -1 & \end{pmatrix}$$

→ Maximally Entangled

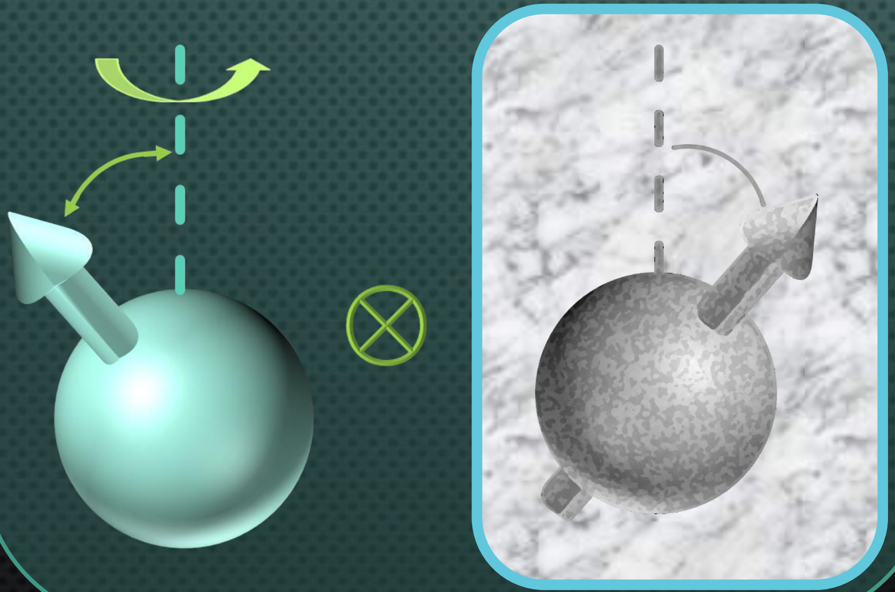
CNOT as entangling operator

Entanglement modifications are state dependent

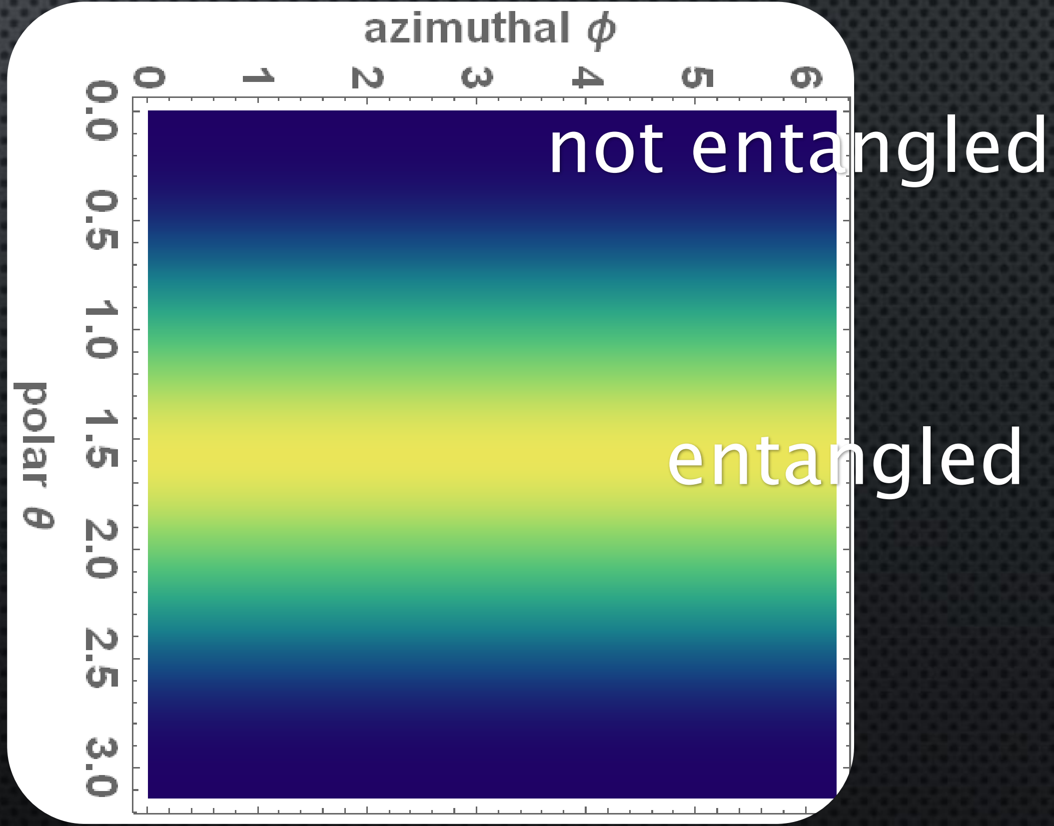


$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

$|\psi\rangle \otimes$ fixed

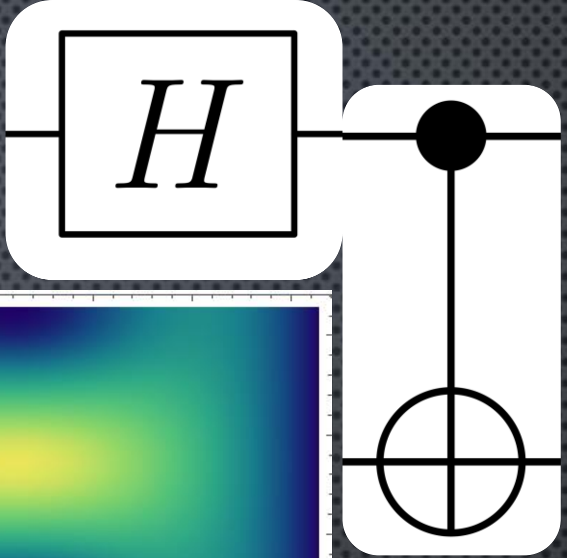


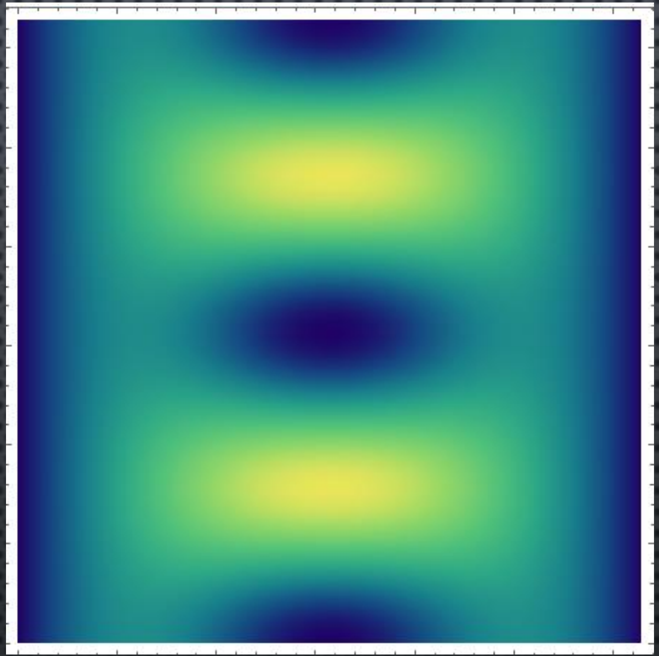
$$1 - Tr({\rho_1}^2)$$

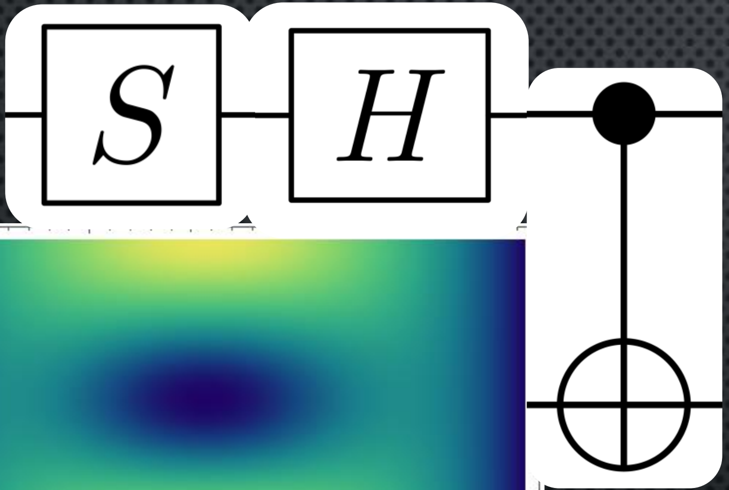


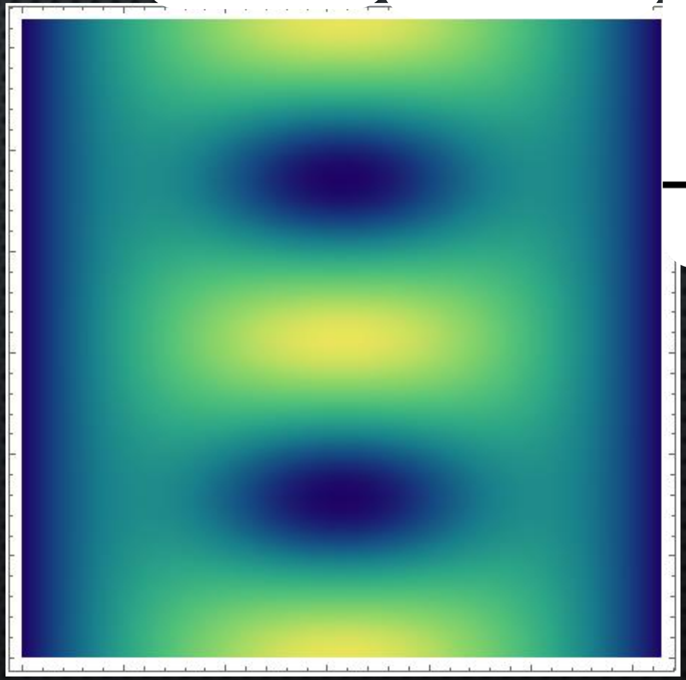
Entangling Power

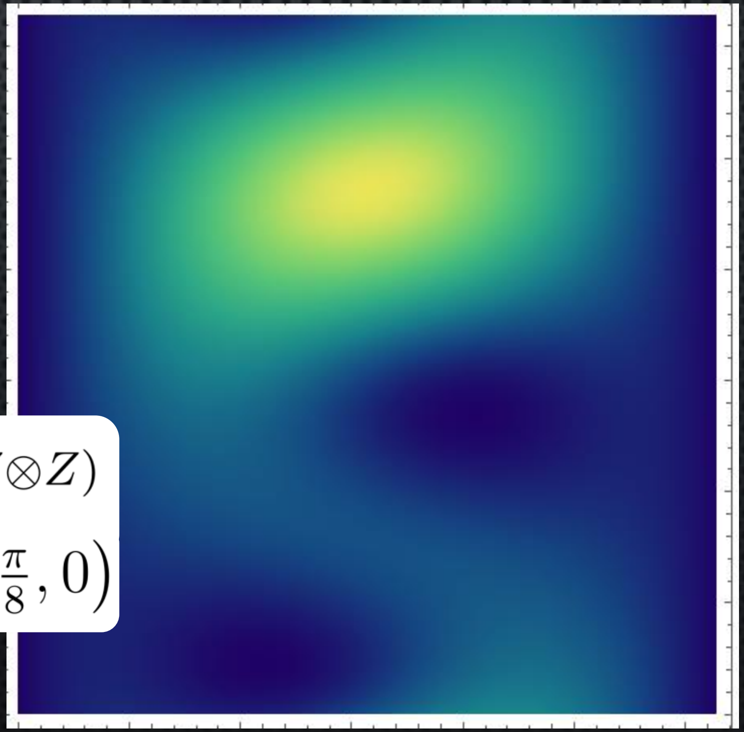
$$\mathcal{E}(\hat{\mathbf{S}}) = 1 - \int \frac{d\Omega_1}{4\pi}\, \frac{d\Omega_2}{4\pi}\, \mathrm{Tr}_1 \left[\, \hat{\rho}_1^2 \,\right]$$





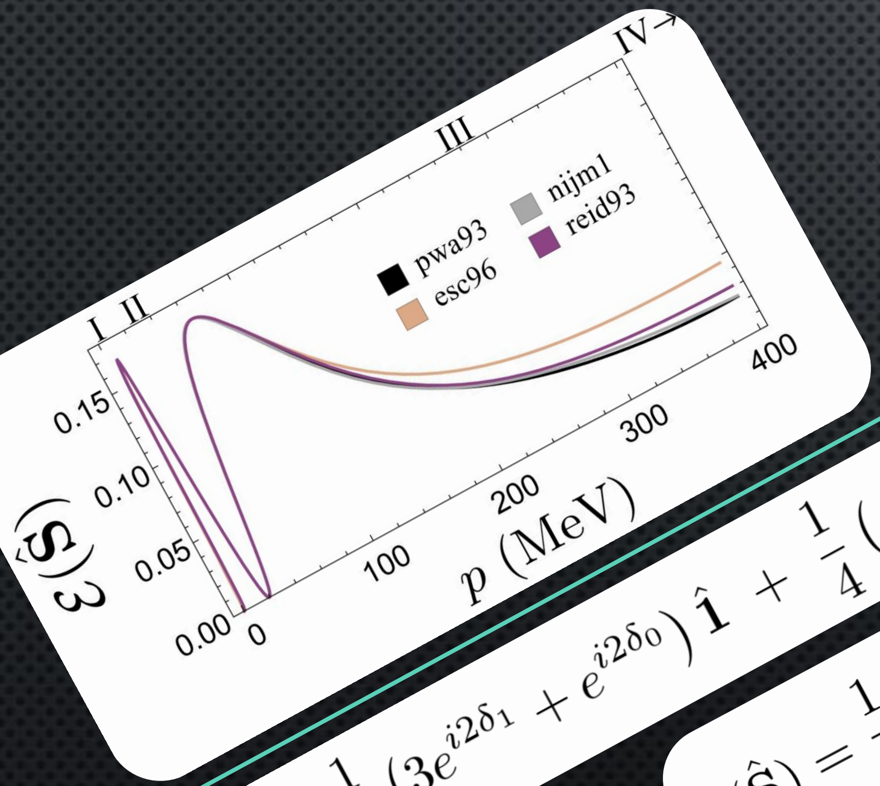






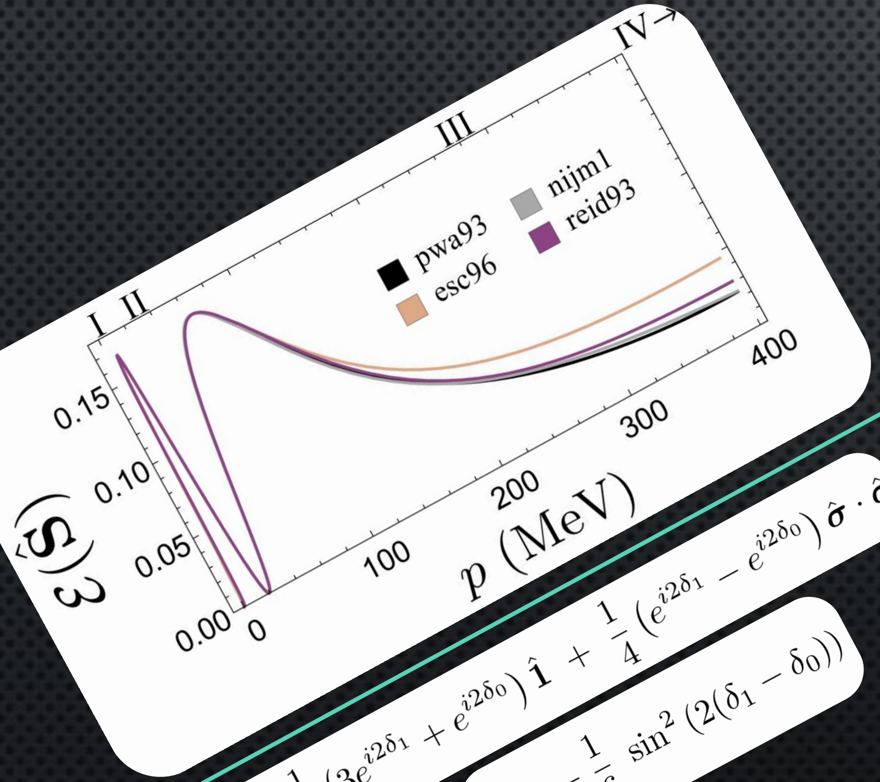
$$U = e^{-i(c_1 X\otimes X + c_2 Y\otimes Y + c_3 Z\otimes Z)}$$

$$(c_1, c_2, c_3) = \left(\frac{\pi}{4}, \frac{\pi}{8}, 0\right)$$



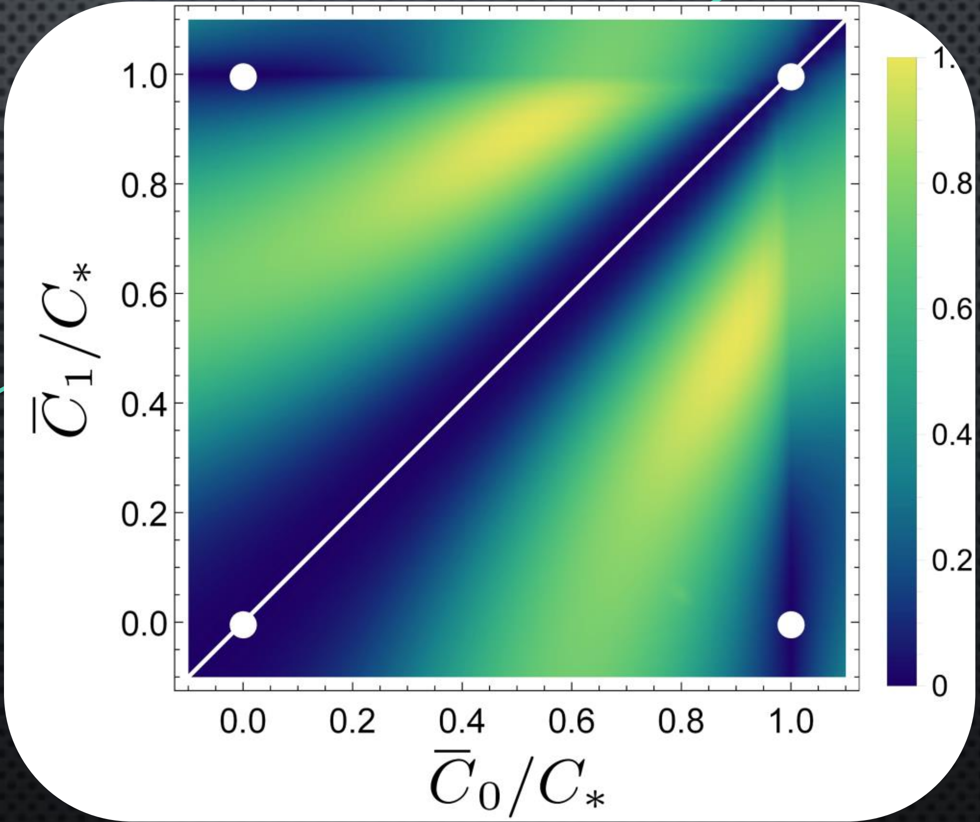
$$\hat{\mathbf{S}} = \frac{1}{4}\left(3e^{i2\delta_1} + e^{i2\delta_0}\right)\hat{\mathbf{1}} + \frac{1}{4}\left(e^{i2\delta_1} - e^{i2\delta_0}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}}$$

$$\mathcal{E}(\hat{\mathbf{S}}) = \frac{1}{6}\ \sin^2\left(2(\delta_1 - \delta_0)\right)$$



$$\hat{\mathbf{S}} = \frac{1}{4}\left(3e^{i2\delta_1} + e^{i2\delta_0}\right)\hat{\mathbf{1}} + \frac{1}{4}\left(e^{i2\delta_1} - e^{i2\delta_0}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}}$$

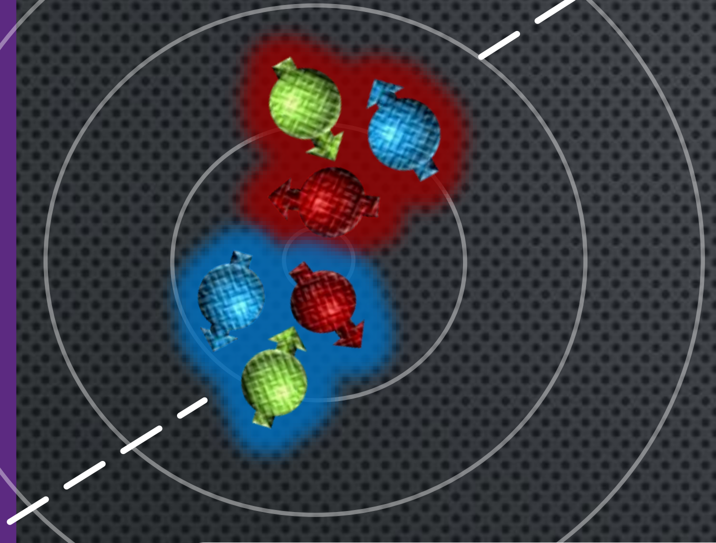
$$\mathcal{E}(\hat{\mathbf{S}}) = \frac{1}{6}\,\sin^2\left(2(\delta_1 - \delta_0)\right)$$



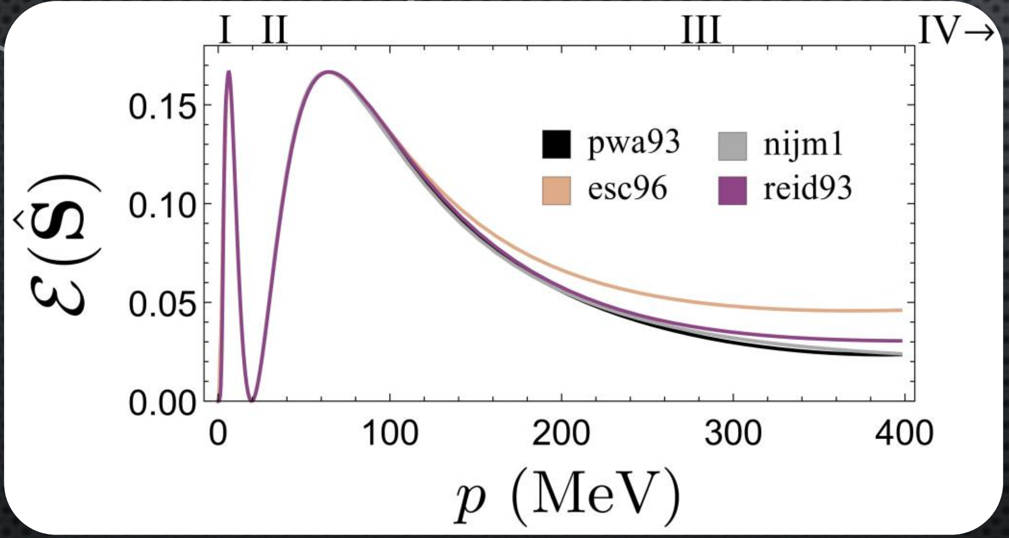
$$\mathcal{L}_{\rm LO}^{n_f=2} = -\frac{1}{2}C_S(N^\dagger N)^2 - \frac{1}{2}C_T\left(N^\dagger\boldsymbol{\sigma}N\right)\cdot\left(N^\dagger\boldsymbol{\sigma}N\right)$$

$$\overline{C}_0 = (C_S - 3C_T)$$

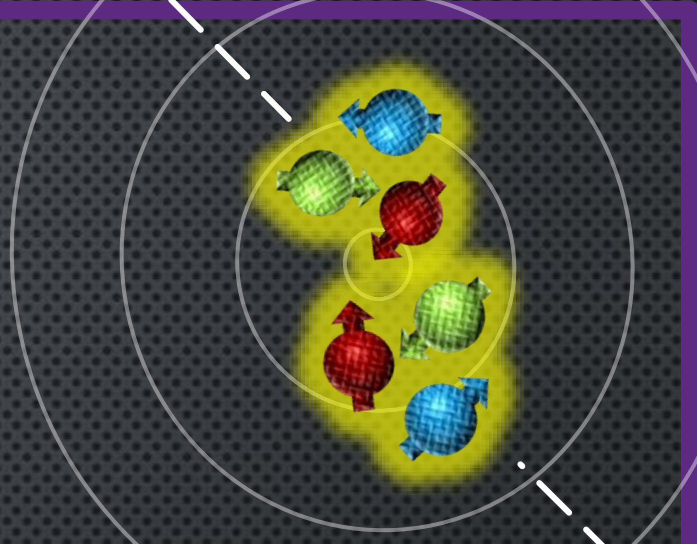
$$\overline{C}_1 = (C_S + C_T)$$



2-flavor SU(4)



3-flavor SU(16)



Baryon-baryon interactions and spin-flavor symmetry from lattice quantum chromodynamics

Michael L. Wagman, Frank Winter, Emmanuel Chang, Zohreh Davoudi, William Detmold, Kostas Orginos, Martin J. Savage, and Phiala E. Shanahan (NPLQCD Collaboration)

Phys. Rev. D **96**, 114510 – Published 28 December 2017

Leading Order in Suppressed Entanglement

$$\mathcal{L}_{\mathrm{LO}}^{n_f=3} \to -\frac{1}{2} c_S \left(\mathcal{B}^\dagger \mathcal{B}\right)^2 , \quad \mathcal{B} = \left(p_\uparrow, p_\downarrow, n_\uparrow, n_\downarrow, \Lambda_\uparrow, \ldots\right)^T$$

Conjecture: dynamical suppression of entanglement fluctuations is an infrared feature of strong interactions producing otherwise-unexpected emergent symmetries

Wait…

EFT hierarchy

$$\varepsilon \ll 1$$

$$\varepsilon \sim \frac{M}{\Lambda}$$

…where is the scale/expansion parameter?

Vacuum Field Entanglement

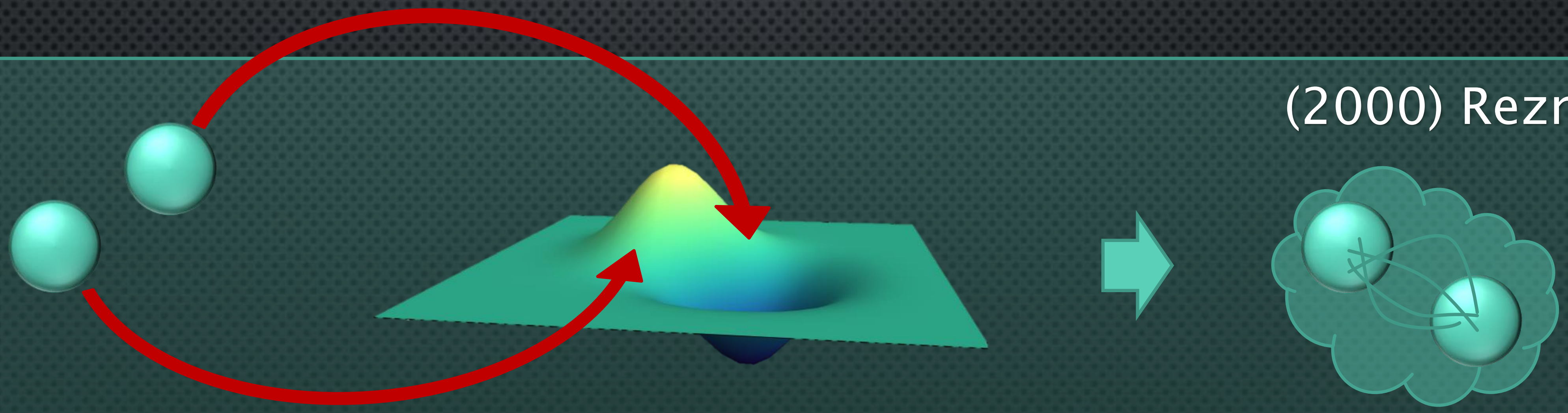
(1961) Reeh-Schlieder

only if $|\chi\rangle = 0$

$$\langle\chi|\phi(x_1)\phi(x_2)\cdots\phi(x_n)|\Omega\rangle \neq 0, \quad x_1,\ldots,x_n \in \mathcal{U}_\mathcal{V}$$

Dense exploration of the field vacuum sector through <u>local operators</u> on the vacuum

(2000) Reznik



Distillation of vacuum entanglement to EPR pairs

G. Vidal; R. F. Werner (2002)
"A computable measure of entanglement"
Phys. Rev. A. **65**: 032314.

Negativity

Entanglement Monotone: non-increasing under local ops.
Sufficient though not necessary for indicating entanglement
Upper bound to distillable entanglement

$$(\rho_{AB})^{\Gamma_B} < 0$$

Heralds non-separability

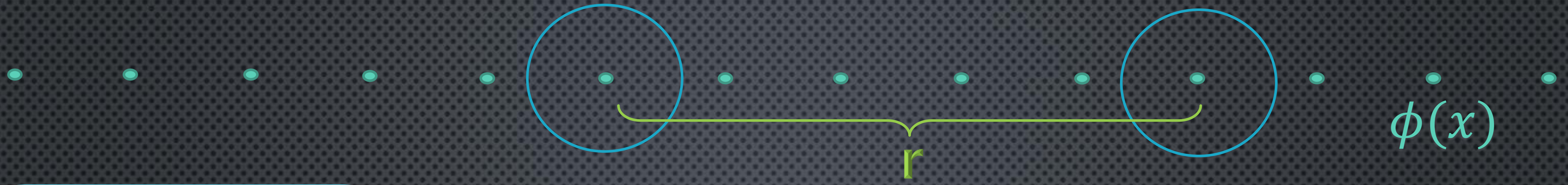
Density Matrices Positive Definite:

$$\rho > 0 \quad \rho^T > 0$$

$$\rho_A \otimes \rho_B > 0$$

Partial Transpose

$$\rho_A \otimes (\rho_B)^T = (\rho_A \otimes \rho_B)^{\Gamma_B} > 0$$



Ground State

$$\langle \phi_0, \phi_1, \cdots, \phi_{N-1} | \psi_0 \rangle = \frac{\det \mathbf{K}^{1/4}}{\pi^{N/4}} e^{-\frac{1}{2}\boldsymbol{\phi}^T \mathbf{K} \boldsymbol{\phi}}$$

$$m \neq 0$$

$$K \sim e^{-mr}$$

$$m = 0$$

$$\langle \phi_1 \phi_2 \rangle \qquad \mathcal{N}$$

$$e^{-mr}$$

Ground State

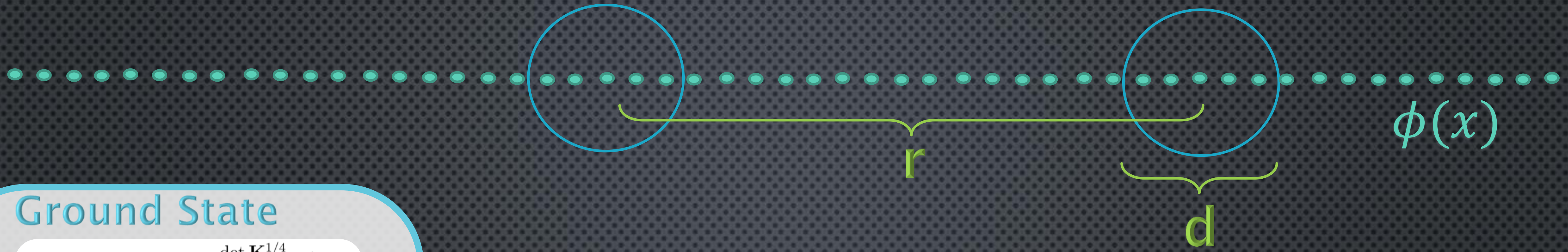
$$\langle \phi_0, \phi_1, \cdots, \phi_{N-1} | \psi_0 \rangle = \frac{\det \mathbf{K}^{1/4}}{\pi^{N/4}} e^{-\frac{1}{2}\boldsymbol{\phi}^T \mathbf{K} \boldsymbol{\phi}}$$

$$m \neq 0$$

$$K \sim e^{-mr}$$

$$m = 0$$

$\langle \phi_1 \phi_2 \rangle$	$\mathcal{N}$
e^{-mr}	0



Ground State

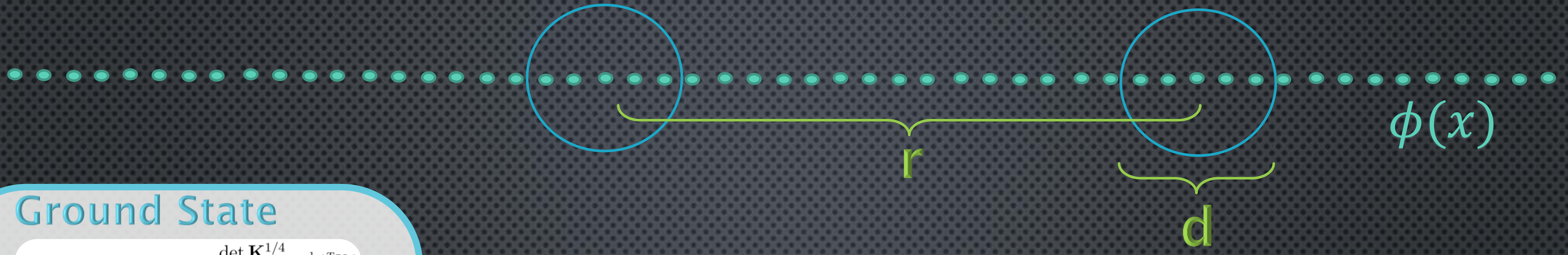
$$\langle \phi_0, \phi_1, \cdots, \phi_{N-1} | \psi_0 \rangle = \frac{\det \mathbf{K}^{1/4}}{\pi^{N/4}} e^{-\frac{1}{2}\phi^T \mathbf{K} \phi}$$

$$m \neq 0$$

$$K \sim e^{-mr}$$

$$m = 0$$

$\langle \phi_1 \phi_2 \rangle$	$\mathcal{N}_{UV}$	$\mathcal{N}_{IR}$
e^{-mr}	0	$e^{-m'r}$



Ground State

$$\langle \phi_0, \phi_1, \cdots, \phi_{N-1} | \psi_0 \rangle = \frac{\det \mathbf{K}^{1/4}}{\pi^{N/4}} e^{-\frac{1}{2}\phi^T \mathbf{K} \phi}$$

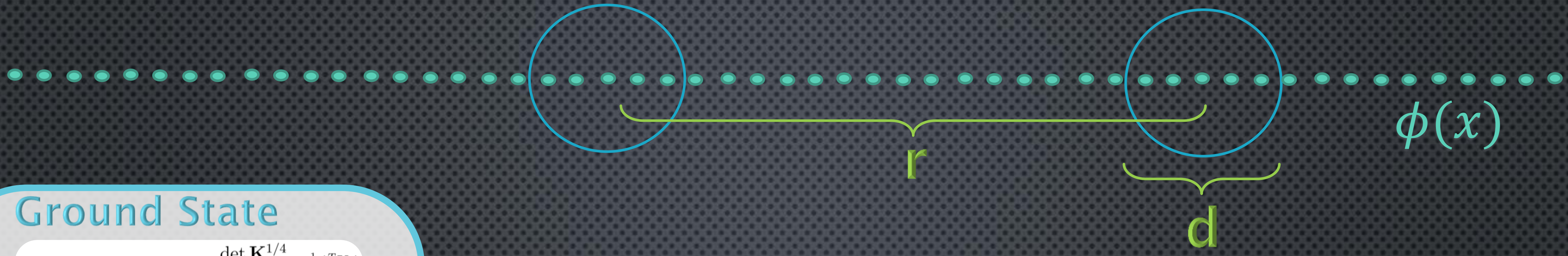
$m \neq 0$

$$K \sim e^{-mr}$$

$m = 0$

$$K \sim r^{-2}$$

$\langle \phi_1 \phi_2 \rangle$	$\mathcal{N}_{UV}$	$\mathcal{N}_{IR}$
e^{-mr}	0	$e^{-m'r}$
$\log(r)$	0	



Ground State

$$\langle \phi_0, \phi_1, \cdots, \phi_{N-1} | \psi_0 \rangle = \frac{\det \mathbf{K}^{1/4}}{\pi^{N/4}} e^{-\frac{1}{2}\phi^T \mathbf{K} \phi}$$

$$m \neq 0$$

$$K \sim e^{-mr}$$

$$m = 0$$

$$K \sim r^{-2}$$

$\langle \phi_1 \phi_2 \rangle$	$\mathcal{N}_{UV}$	$\mathcal{N}_{IR}$
e^{-mr}	0	$e^{-m'r}$
$\log(r)$	0	$e^{-\beta \frac{r}{d}}$

Ground State

$$\langle \phi_0, \phi_1, \cdots, \phi_{N-1} | \psi_0 \rangle = \frac{\det \mathbf{K}^{1/4}}{\pi^{N/4}} e^{-\frac{1}{2}\phi^T \mathbf{K} \phi}$$

$m \neq 0$

$K \sim e$

$m = 0$

$K \sim r^{-}$

$e^{-\beta\frac{r}{d}}$

Pure number: Negativity Decay Constant

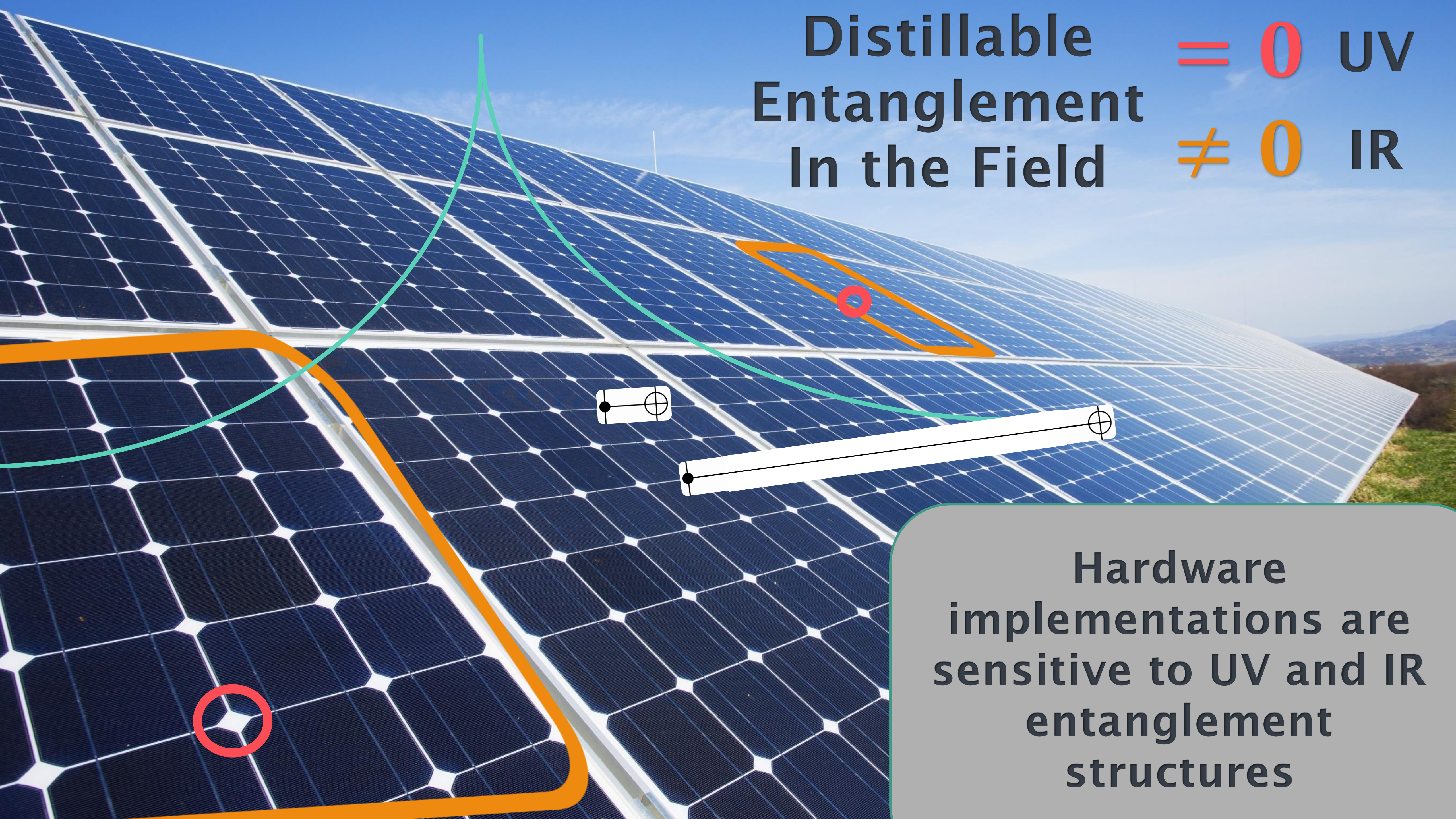
Exponentially localizes specifically quantum correlations

$\beta_{1D} \sim 2.82(3)$

Marcovitch et. al. (2009)

$\beta_{2D} \sim 5.29(4)$

NK, Savage (2020)


Distillable Entanglement In the Field
$= 0$ UV
$\neq 0$ IR
Hardware implementations are sensitive to UV and IR entanglement structures

Summary

- Understanding the role of entanglement in subatomic interactions is expected to provide **deeper natural insights**, as well as inform their successful simulation on atomic-scale quantum architectures

- Field theories provide a **natural language** for the design of quantum simulations and large-scale quantum computing

- Formulating a calculation for QC requires **new perspectives** on the roles of measurements, entanglement structure, superposition, and interference as computational resources.

- The NISQ era creates small devices to **begin developing intuition and identifying important features** for Physics applications on future fault tolerant devices.

UW collaborators:

Silas Beane
David Kaplan
Kenneth Roche
Alessandro Roggero
Martin Savage
Jesse Stryker