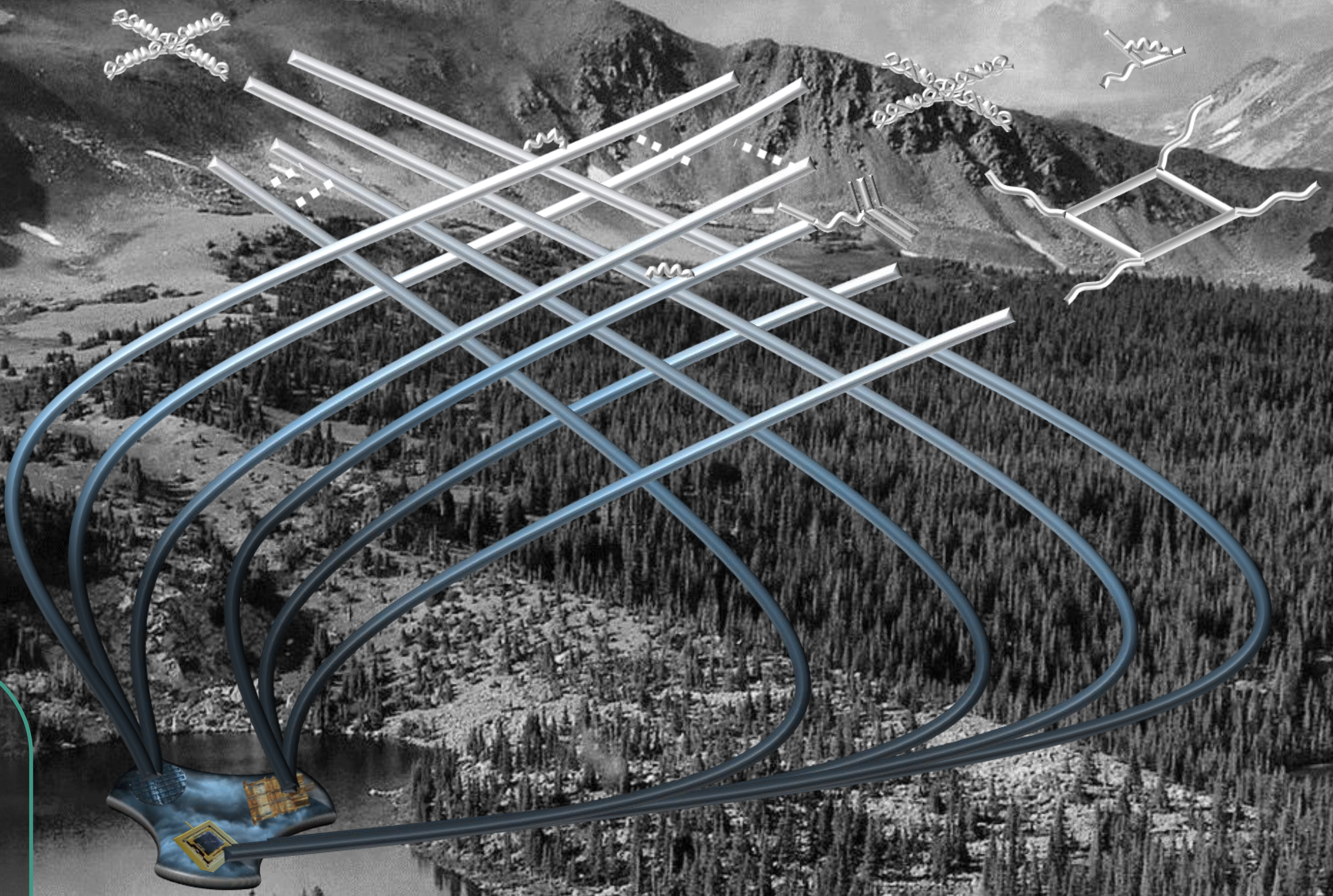


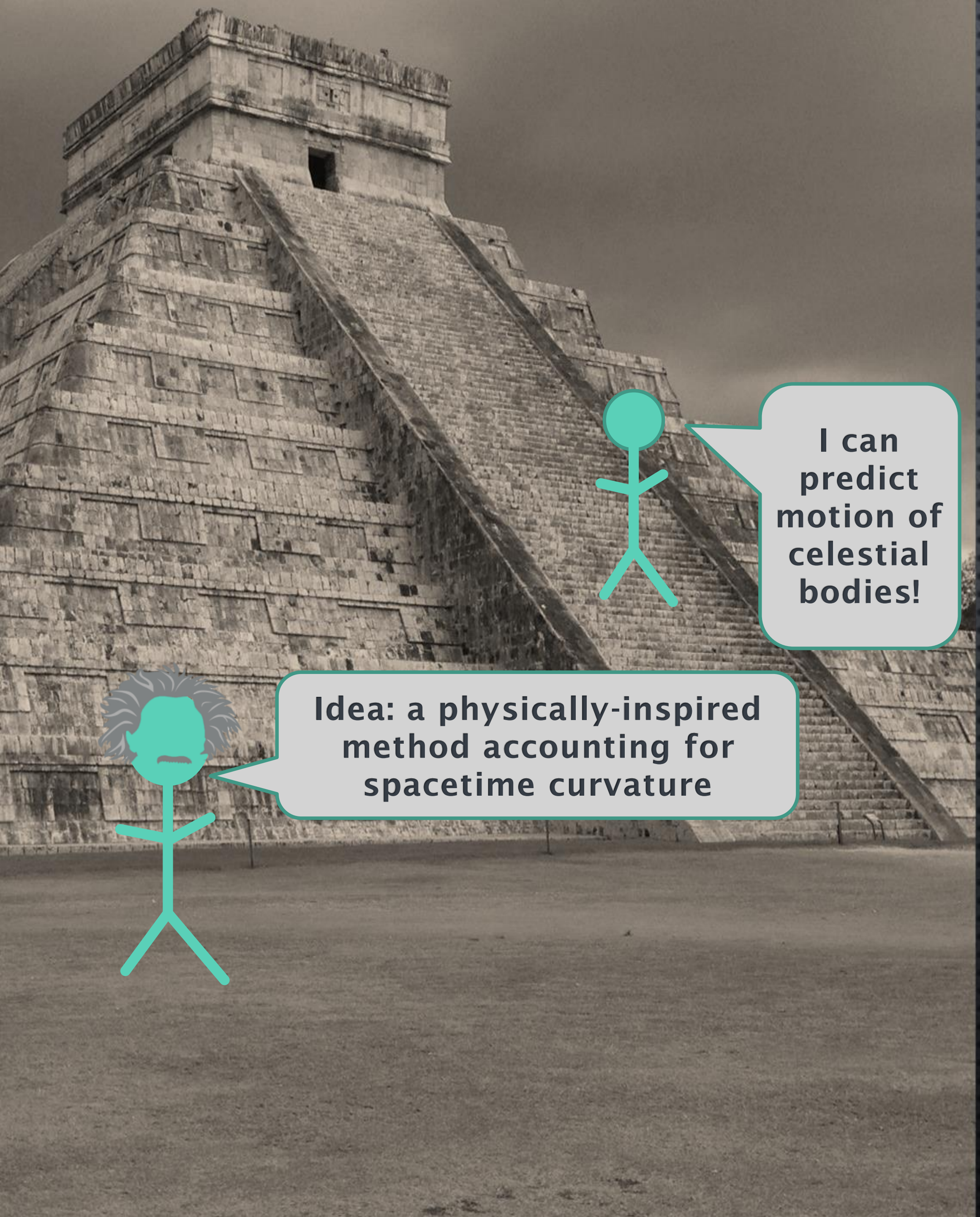
Musings on the Intersimulatability of Quantum Fields

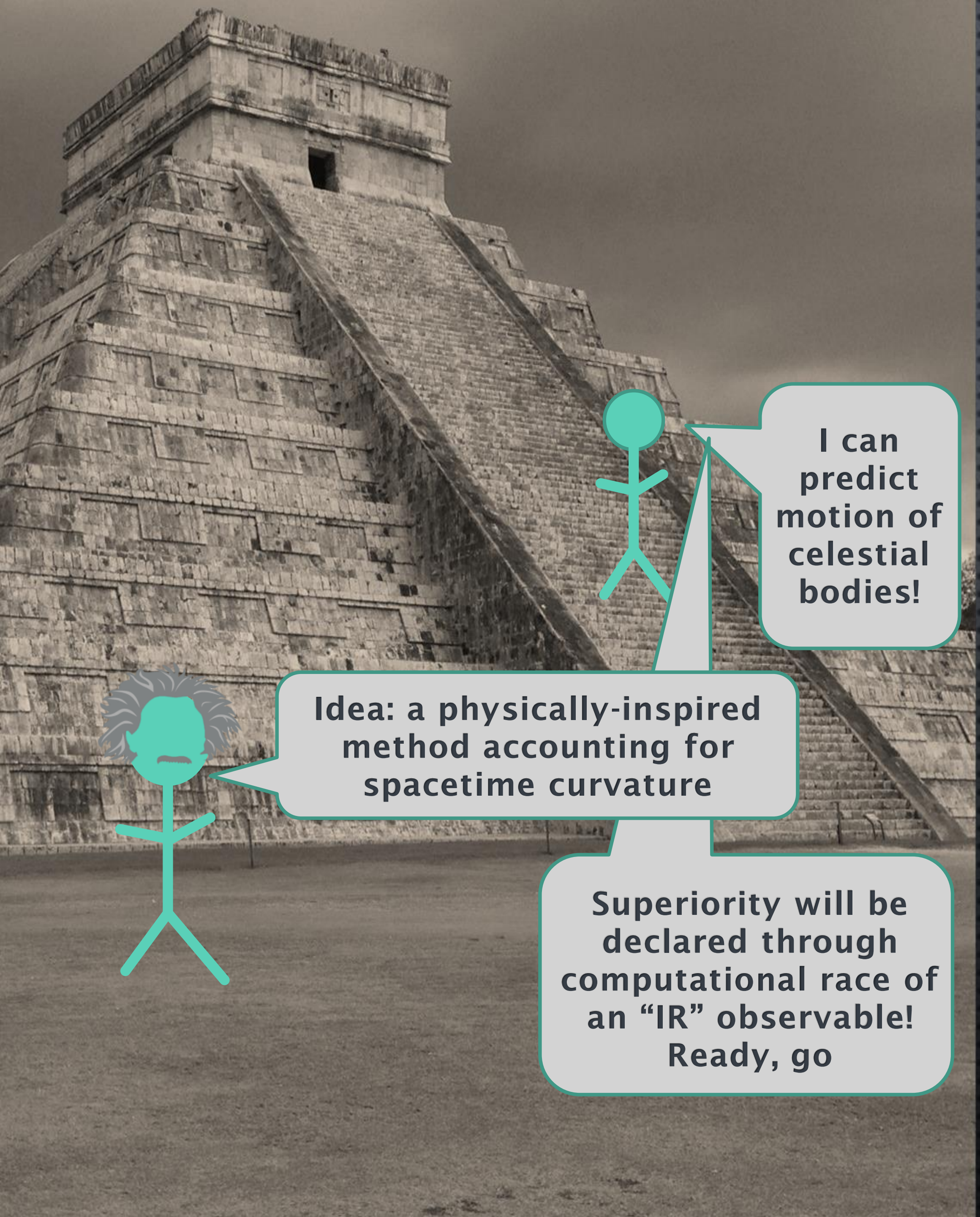
ECT* Workshop
Advances in Many-Body Theories

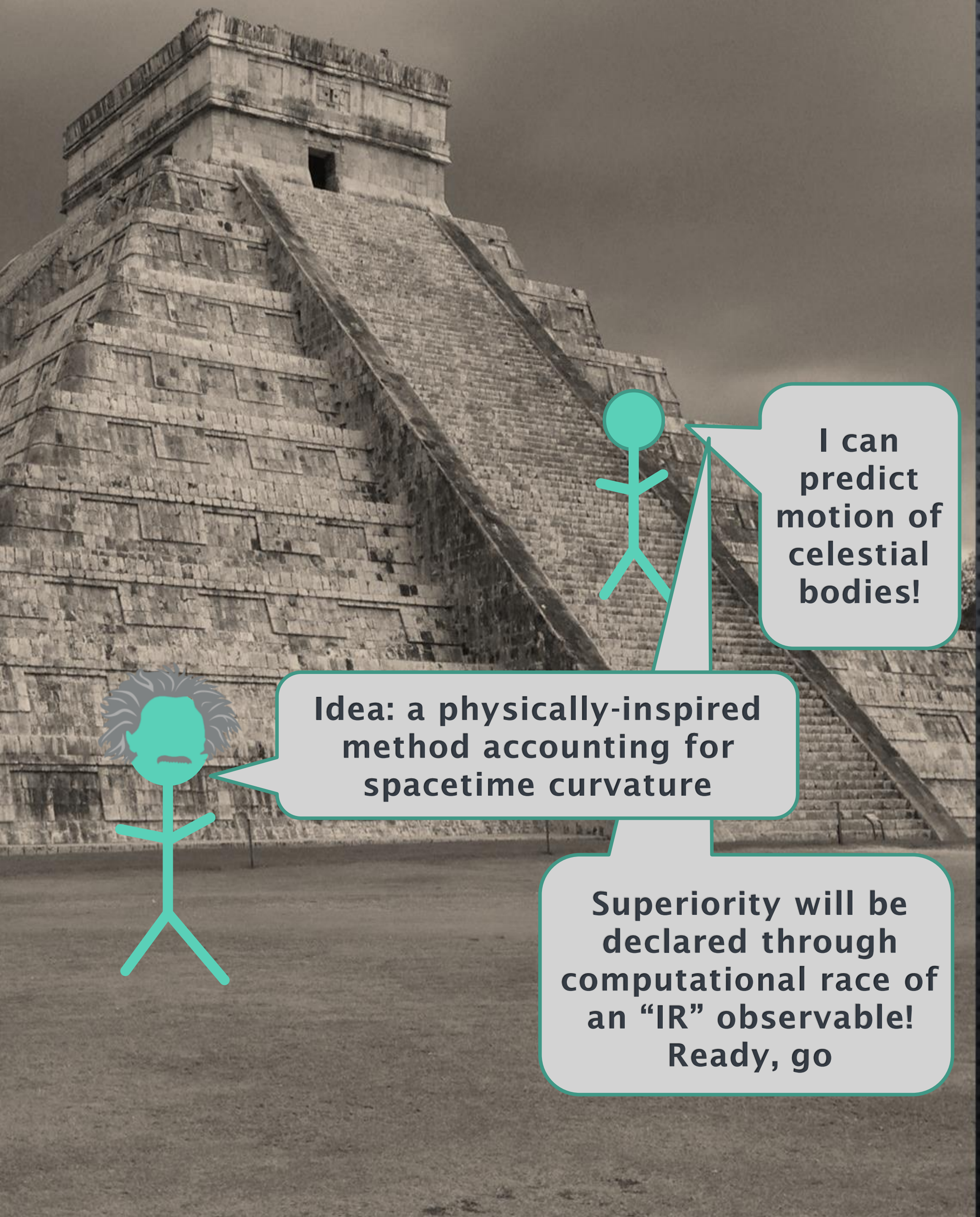
Trento, Italy. November 2nd 2020

IQIM
California Institute of Technology 1891
Natalie Klco
Burke Institute


I can predict motion of celestial bodies!


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

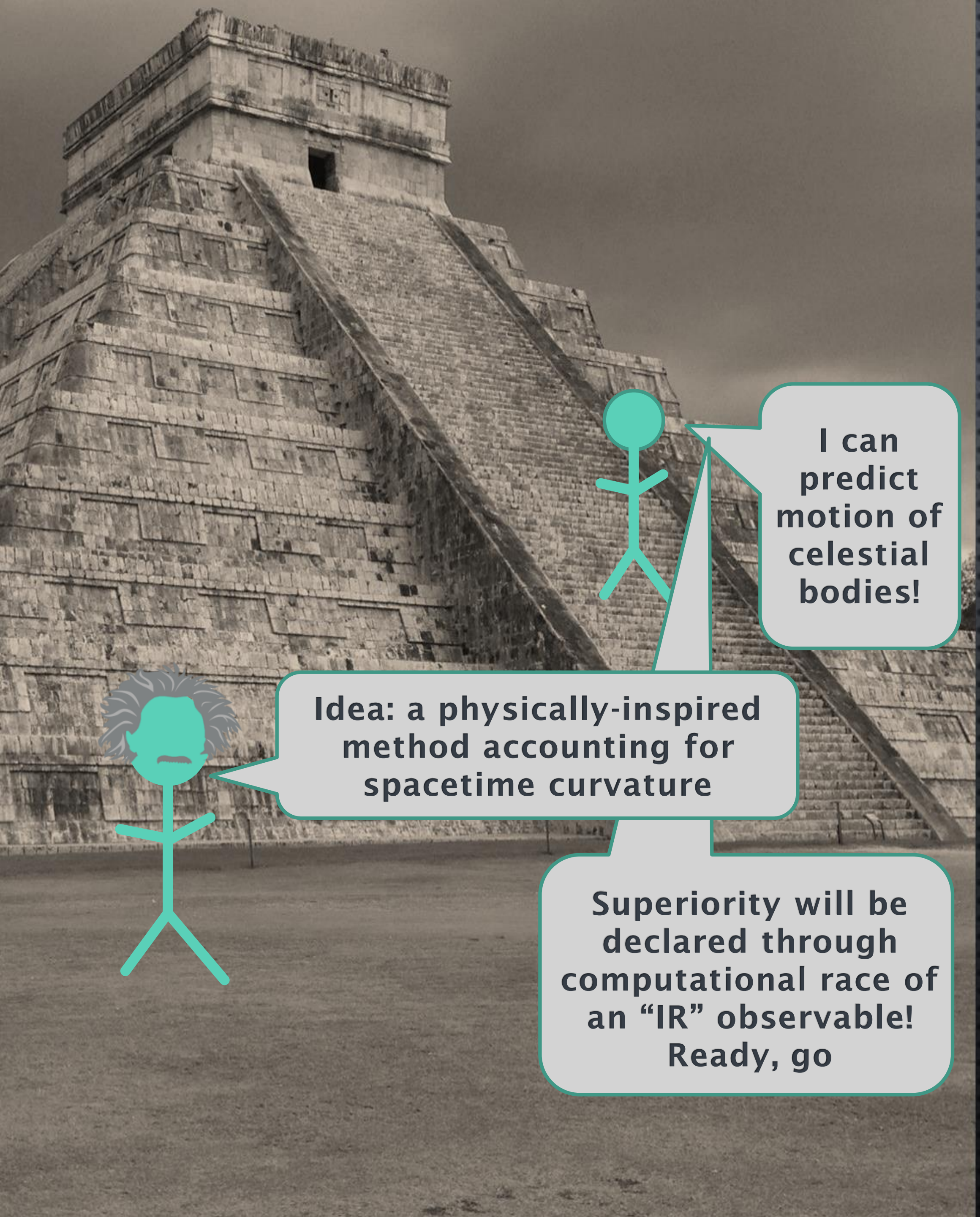

I can predict motion of celestial bodies!
Idea: a physically-inspired method accounting for spacetime curvature
Superiority will be declared through computational race of an “IR” observable! Ready, go



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



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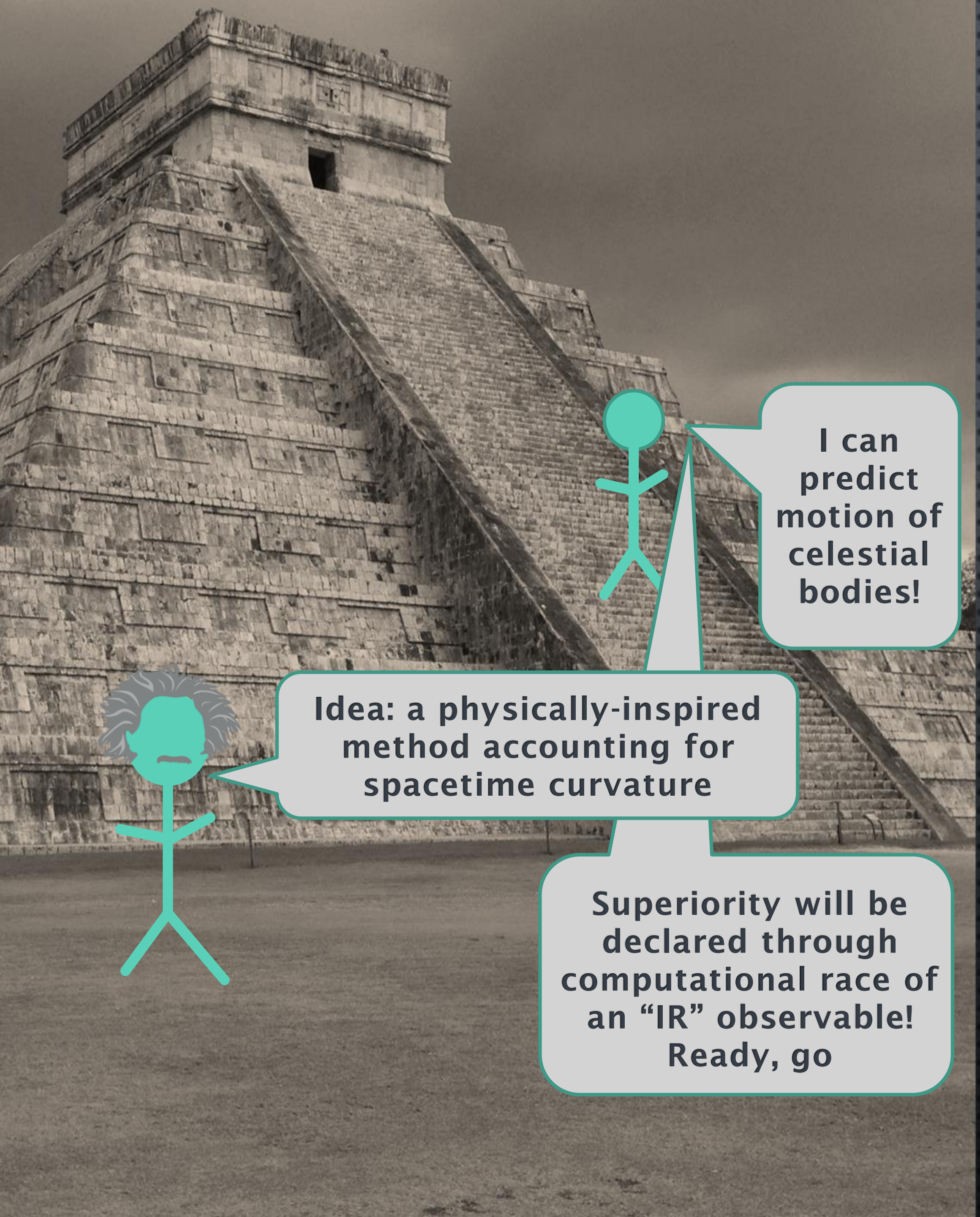
Historically rare for a dramatic restructuring of a computational framework to be embraced before scientifically-relevant supremacy is proven.



Calculating Nature Naturally

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

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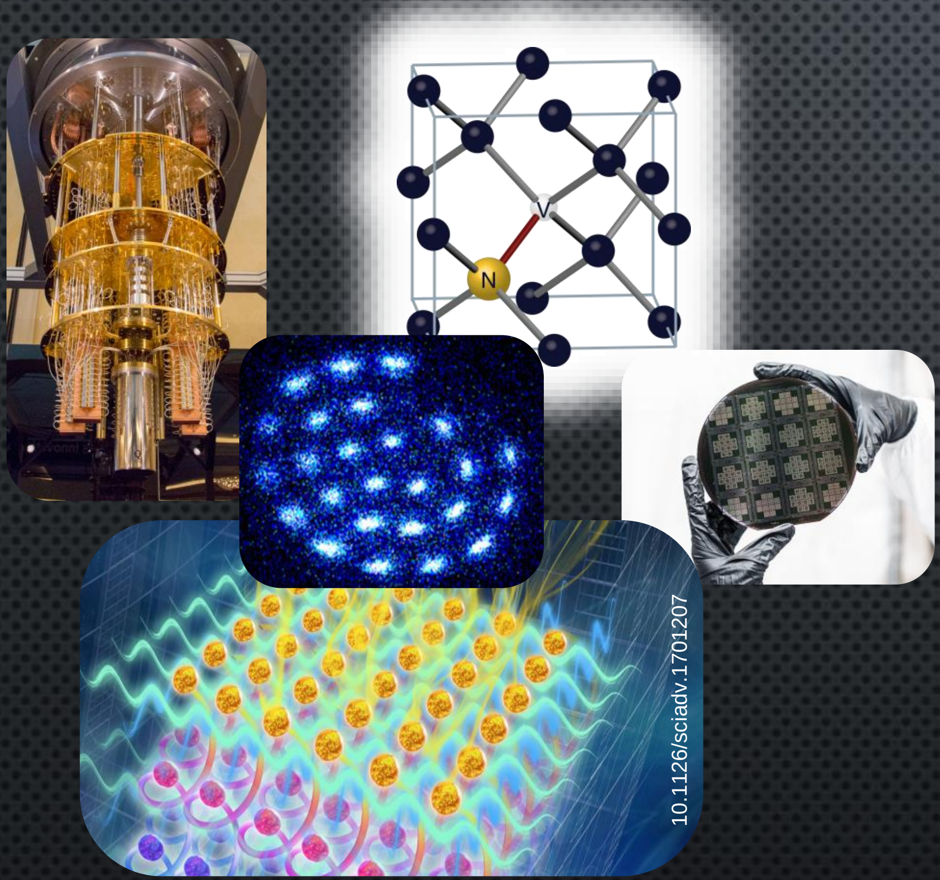
Historically rare for a dramatic restructuring of a computational framework to be embraced before scientifically-relevant supremacy is proven.

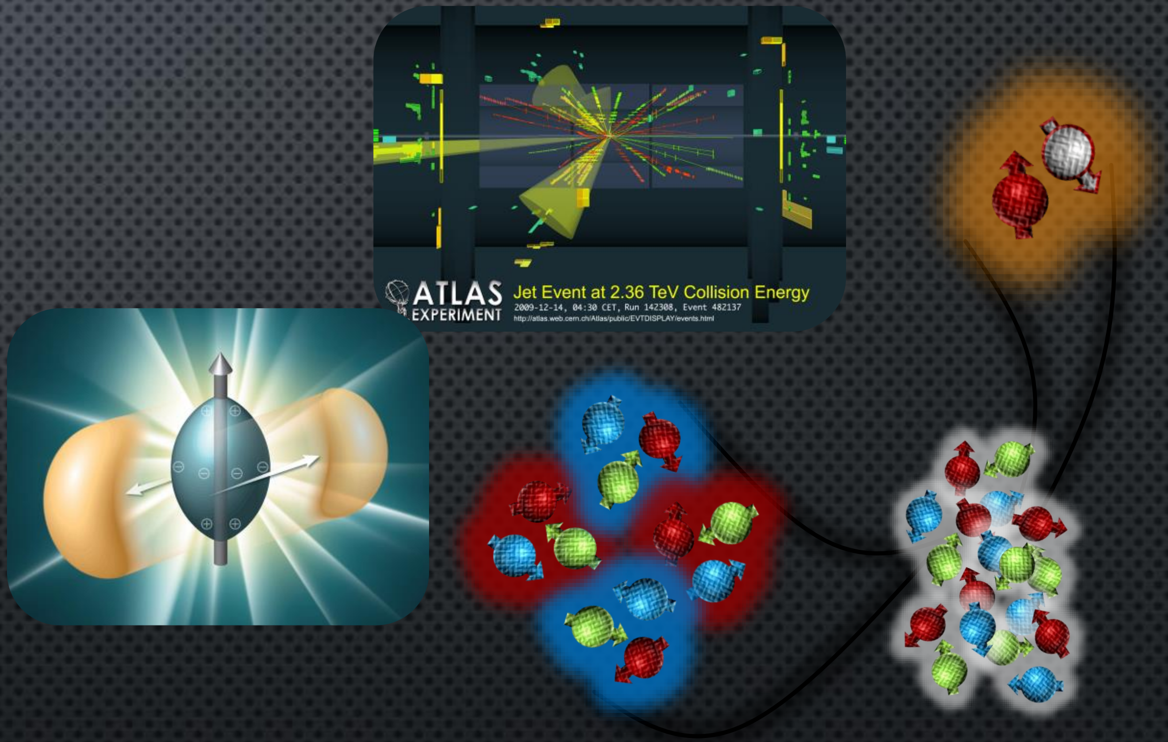
~~Whim~~ Inevitable Progression of Research:

- ~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 World is "Mutually Intersimulatable"

–Feynman



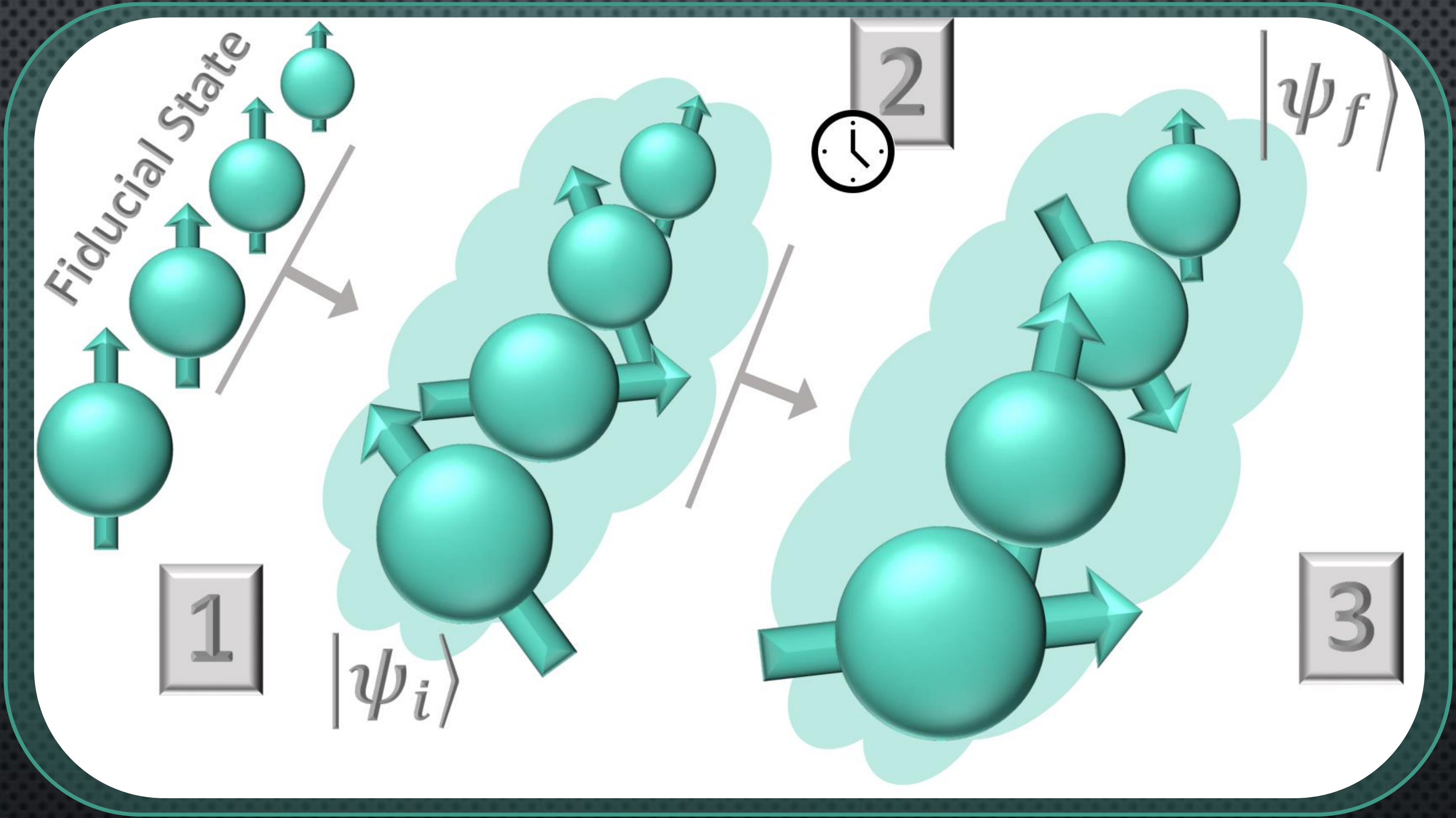


Processing of quantum information

Allow efficient exploration of the interactions of subatomic degrees of freedom with controllable atomic-scale quantum architectures.

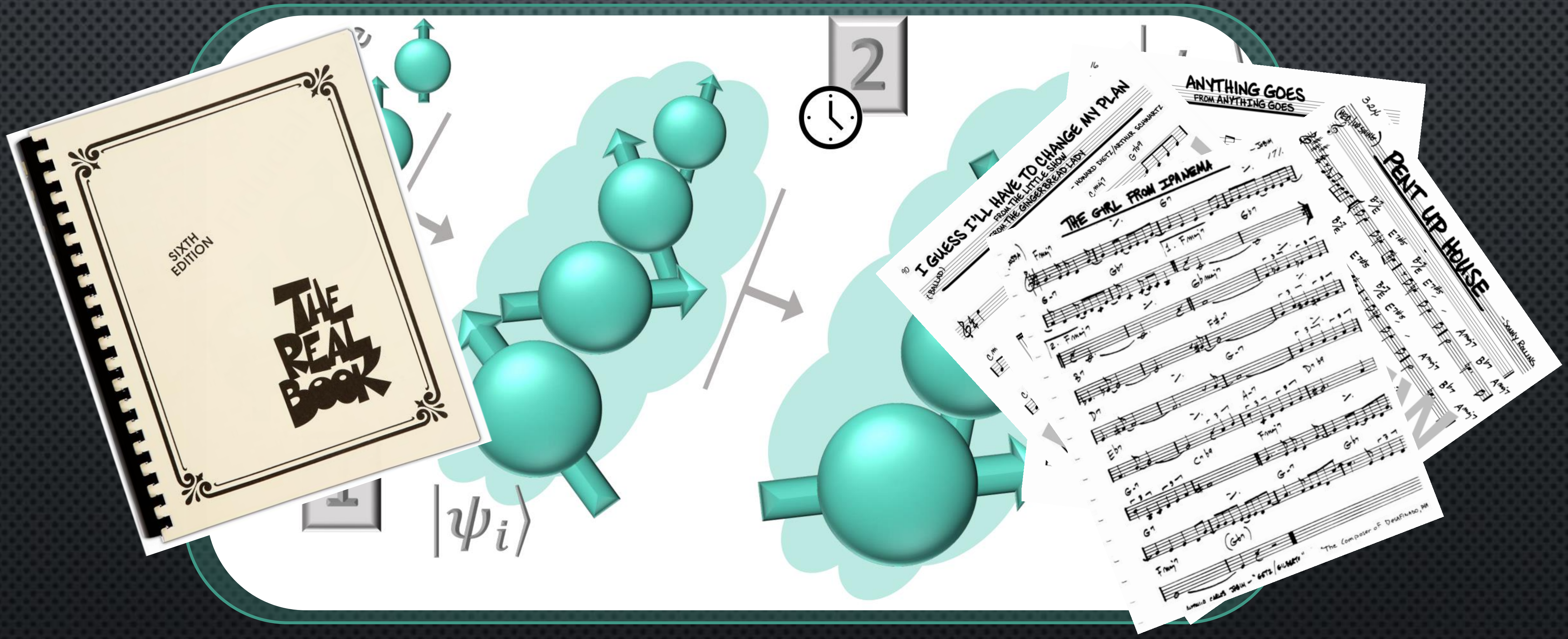
Quantum Simulation 101

State Preparation---Time Evolution---Measurement



Quantum Simulation 101

State Preparation---Time Evolution---Measurement



Nothing is Sacred

...except for experimentally verified laws of physics

Simulation D.o.F. → Hardware D.o.F.

“basis”

What will the Hilbert space mean?

Simulation D.o.F. → Hardware D.o.F.

"basis"

What will the Hilbert space mean?

Analog

- robust, reliable, and available historically earlier than their digital counterparts
- quantum system tuned to emulate relevant dynamics with natural time evolution
- "Computing through Simile"

Digital

- Flexible language
- Digitized errors

Language is a filter capable of both distorting and sharpening the development of ideas

Codesign Combinations

- Digital-Analog
- Quantum-Classical

Codesign Question:

Where is the Line?
Is there a Line?

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

(1998) Gottesman-Knill Theorem:

- Stabilizer circuits classically simulated in polynomial time.
- Entanglement is not a sufficient criteria for complexity.

Entanglement (huh)

……What is it good for?

Absolutely Something

Stabilizer

$$P|\psi_S\rangle = |\psi_S\rangle$$

$$|S(|\psi\rangle)| = 2^n$$

Stabilizers succinctly described by n generators

$$\pm\,\sigma_1 \otimes \sigma_2 \otimes \cdots \otimes \sigma_n$$

$(1 + 2n)n$ bits

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$$|\psi_S\rangle : \{P_1, P_2, \dots, P_n\}$$

$$U|\psi_S\rangle = \{UP_1U^\dagger, UP_2U^\dagger, \dots, UP_nU^\dagger\}$$

$$U|\psi_S\rangle = \{P'_1, P'_2, \dots, P'_n\}$$

$$UPU^\dagger = P'$$

$$U = \{H, S, CNOT, X, Y, Z\}$$

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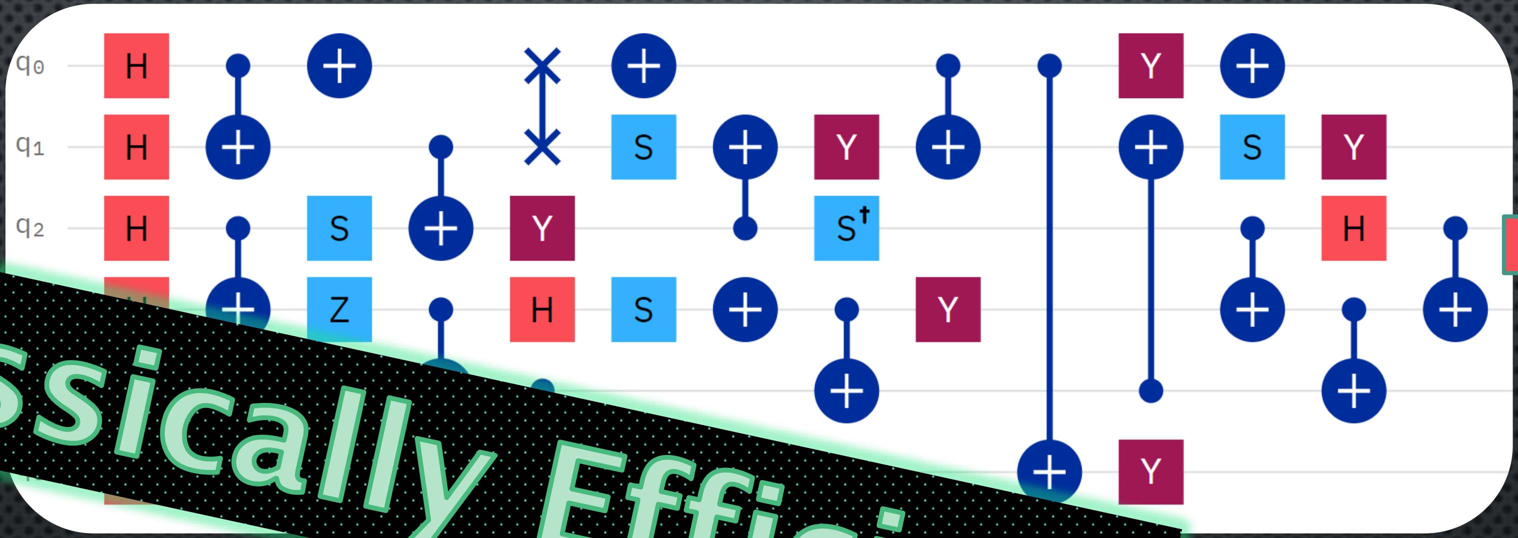
$$UPU^\dagger = P'$$

$$U = \{H, S, CNOT, X, Y, Z\}$$

$$TPT^\dagger = \sum P'$$

Entanglement ~ Complexity?

Not quite



Classically Efficient

NP-relevant T-complexities?

- Not Universal: missing T gate

T-gate count meaningful expression of quantum simulation complexity

Tensor Networks as Truncated Entanglement Hierarchy

$$|\Psi\rangle = \sum_{i_1=0}^{1} \cdots \sum_{i_n=0}^{1} c_{i_1 \cdots i_n} |i_1\rangle \otimes \cdots \otimes |i_n\rangle.$$

Schmidt Decomposition

$$|\Psi\rangle = \sum_{\alpha=1}^{\chi_A} \lambda_\alpha |\Phi_\alpha^{[A]}\rangle \otimes |\Phi_\alpha^{[B]}\rangle$$

$$c_{i_1 i_2 \cdots i_n} = \sum_{\alpha_1, \cdots, \alpha_{n-1}} \Gamma^{[1]i_1}_{\alpha_1} \lambda^{[1]}_{\alpha_1} \Gamma^{[2]i_2}_{\alpha_1 \alpha_2} \lambda^{[2]}_{\alpha_2} \Gamma^{[3]i_3}_{\alpha_2 \alpha_3} \cdots \Gamma^{[n]i_n}_{\alpha_{n-1}}.$$

n qubit state $\leftrightarrow$ $n \exp(E\chi)$ parameters.

VOLUME 91, NUMBER 14 — PHYSICAL REVIEW LETTERS — week ending 3 OCTOBER 2003

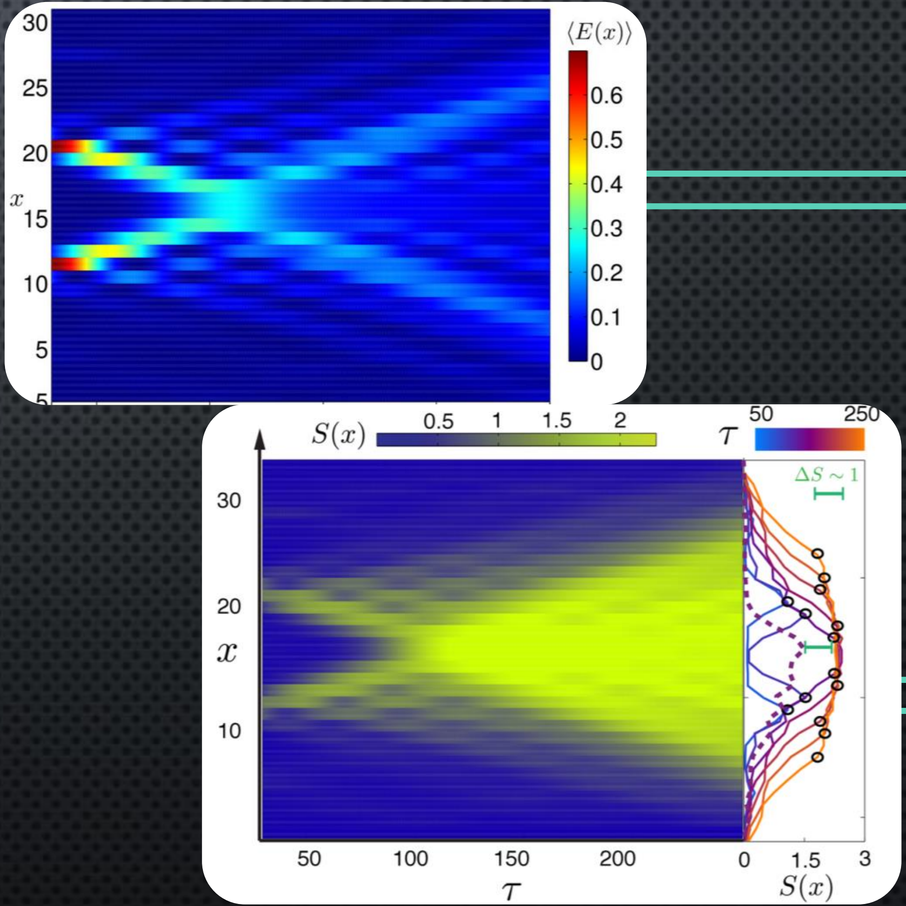
Efficient Classical Simulation of Slightly Entangled Quantum Computations

Guifré Vidal

VOLUME 69, NUMBER 19 — PHYSICAL REVIEW LETTERS — 9 NOVEMBER 1992

Density Matrix Formulation for Quantum Renormalization Groups

Steven R. White



Real-Time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks. Pichler et. al. (2016)

Entropy and Area*
hep-th/9303048
MARK SREDNICKI[†]

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]

Entanglement Entropy and Quantum Field Theory
Pasquale Calabrese[1] and John Cardy[1,2] arXiv:hep-th/0405152v3

On the entanglement entropy for gauge theories
Sudip Ghosh,[a] Ronak M Soni[b] and Sandip P. Trivedi[b] JHEP09(2015)069

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,†]

PHYSICAL REVIEW LETTERS **122,** 102001 (2019)
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]
[1]*Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*

Entanglement Rearrangement in Self-Consistent Nuclear Structure Calculations
Caroline Robin,[1,*] Martin J. Savage,[1,†] and Nathalie Pillet[2] arXiv:2007.09157v1

The silence of binary Kerr arXiv:2007.09486v2
Rafael Aoude,[1] Ming-Zhi Chung,[2] Yu-tin Huang,[2,3] Camila S. Machado,[1] and Man-Kuan Tam[2]

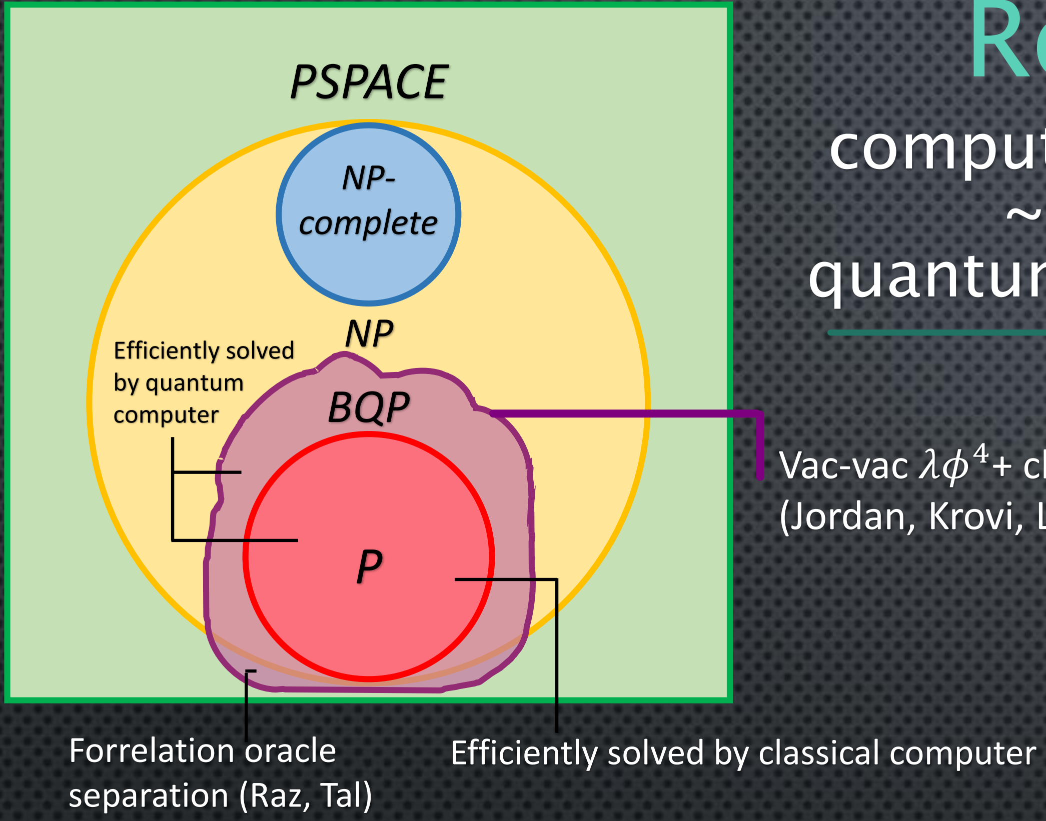
Chiral symmetry breaking, entanglement, and the nucleon spin decomposition
Silas R. Beane[1] and Peter Ehlers[1] arXiv:1905.03295v1

Geometric Quantum Information Structure in Quantum Fields and their Lattice Simulation
Natalie Klco* and Martin J. Savage[†] arXiv:2008.03647v1

Role of Quantum Fields

nature
~
quantum field

Aaronson (Sci. Am.)



Role of Quantum Fields

computation
~
quantum field

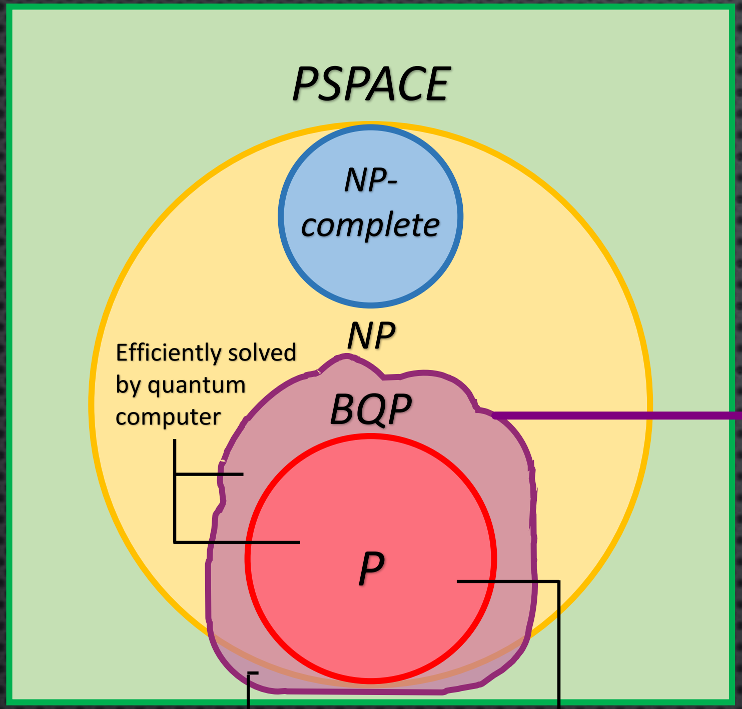
nature
~
quantum field

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

- 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)
  (2002, 2006)

Role of Quantum Fields

Aaronson (Sci. Am.)



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

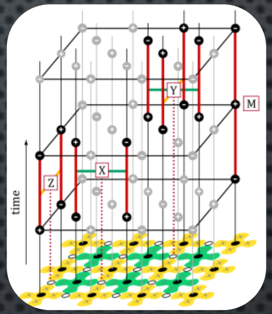
Forrelation oracle separation (Raz, Tal)

Efficiently solved by classical computer

computation ~ quantum field

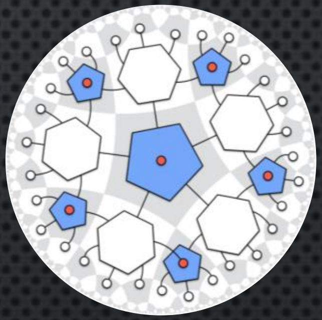
nature ~ quantum field

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)

Vacuum Field Entanglement

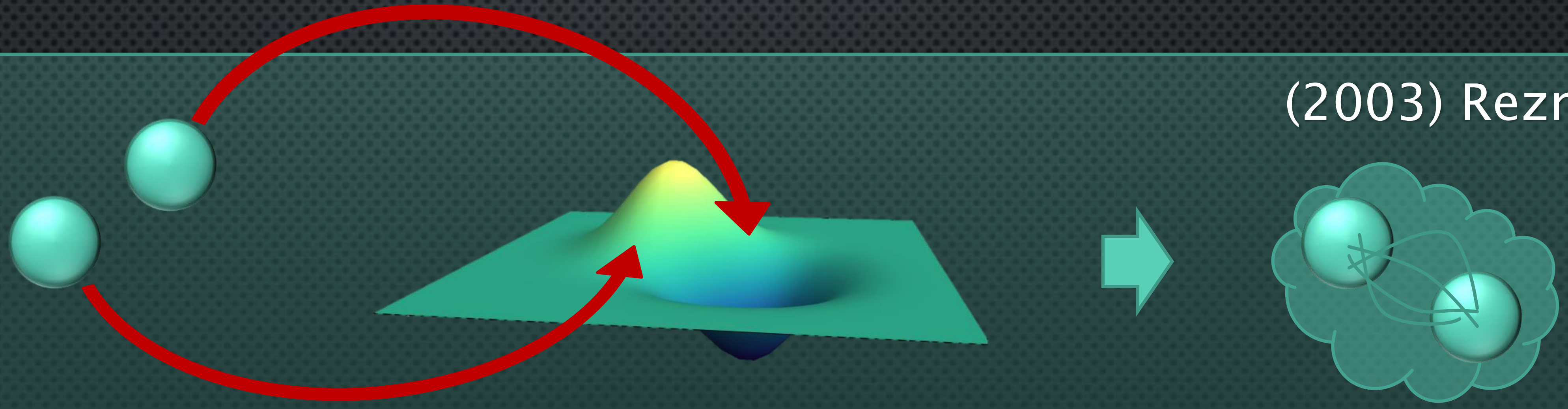
(1961) Reeh-Schlieder

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 local operators on the vacuum

(2003) Reznik

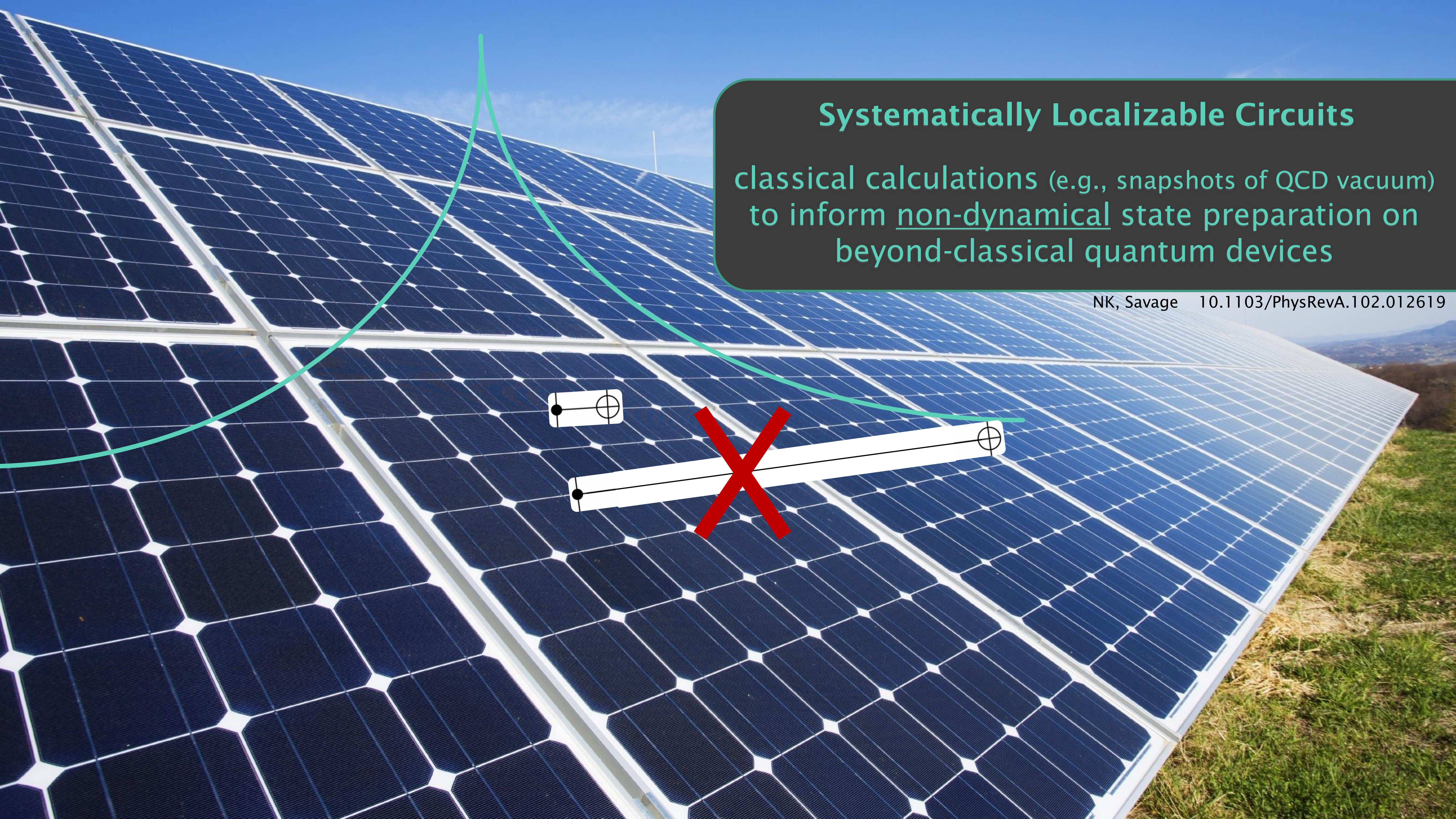


Distillation of vacuum entanglement to EPR pairs

Systematically Localizable Circuits

classical calculations (e.g., snapshots of QCD vacuum)
to inform <u>non-dynamical</u> state preparation on
beyond-classical quantum devices

NK, Savage 10.1103/PhysRevA.102.012619



Distillable Entanglement In the Field

$= 0$ UV

$\neq 0$ IR

Hardware implementations are sensitive to UV and IR entanglement structures

Distillable Entanglement In the Field

Big Hilbert Spaces are Useful

- Commensurate with Physical System
- Quantum Error Correction
- Conserved Quantities (e.g., Chemistry)
- Symmetries, both local and global (e.g., Gauge Theory)

..but needs to be protected

- Software: surface codes with local symmetry
  - Logical qubit embedded into $\sim 10^4$ physical
- Hardware: braiding topological phases of matter
- Software: Holographic codes
- Codesign: Map gauss' law to hardware-conserved quantity
- Codesign: classical error mitigation, post selection, randomization, decoherence-free subspaces…

Metrics Simulations informative

Atomic Quantum Simulation of $U(N)$ and $SU(N)$ Non-Abelian Lattice Gauge Theories

D. Banerjee[1], M. Bögli[1], M. Dalmonte[2], E. Rico[2,3], P. Stebler[1], U.-J. Wiese[1], and P. Zoller[2,3]

Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices

Erez Zohar J. Ignacio Cirac Benni Reznik

05

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

03

Quantum-classical computation of Schwinger model dynamics using quantum computers

N. Klco,[1,*] E. F. Dumitrescu,[2] A. J. McCaskey,[3] T. D. Morris,[4] R. C. Pooser,[2] M. Sanz,[5] E. Solano,[5,6] P. Lougovski,[2,†] and M. J. Savage[1,‡]

Towards analog quantum simulations of lattice gauge theories with trapped ions

Zohreh Davoudi,[1,2] Mohammad Hafezi,[3,4] Christopher Monroe,[3,5] Guido Pagano,[3,5,6] Alireza Seif,[3] and Andrew Shaw[1]

02

SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers

Natalie Klco, Jesse R. Stryker and Martin J. Savage[1]

A scalable realization of local U(1) gauge invariance in cold atomic mixtures

Alexander Mil[1,*], Torsten V. Zache[2], Apoorva Hegde[1], Andy Xia[1], Rohit P. Bhatt[1], Markus K. Oberthaler[1], Philipp Hauke[1,2,3], Jürgen Berges[2], Fred Jendrzejewski[1]

Science 06 Mar 2020:
Vol. 367, Issue 6482, pp. 1128-1130
DOI: 10.1126/science.aaz5312

Quantum simulation of the qubit-regularized $O(3)$ sigma model

Alexander J. Buser
Tanmoy Bhattacharya, Lukasz Cincio, and Rajan Gupta

Real-time chiral dynamics from a digital quantum simulation

Dmitri E. Kharzeev[1,2,3,*] and Yuta Kikuchi[3,†]

A resource efficient approach for quantum and classical simulations of gauge theories in particle physics

Jan F. Haase[1,2], Luca Dellantonio[1,2], Alessio Celi[3,4], Danny Paulson[1,2], Angus Kan[1,2], Karl Jans and Christine A. Muschik[1,2,6]

Optimal control for the quantum simulation of nuclear dynamics

Eric T. Holland, Kyle A. Wendt, Konstantinos Kravvaris, Xian Wu, W. Erich Ormand, Jonathan L DuBois, Sofia Quaglioni, and Francesco Pederiva

Phys. Rev. A **101**, 062307 – Published 3 June 2020

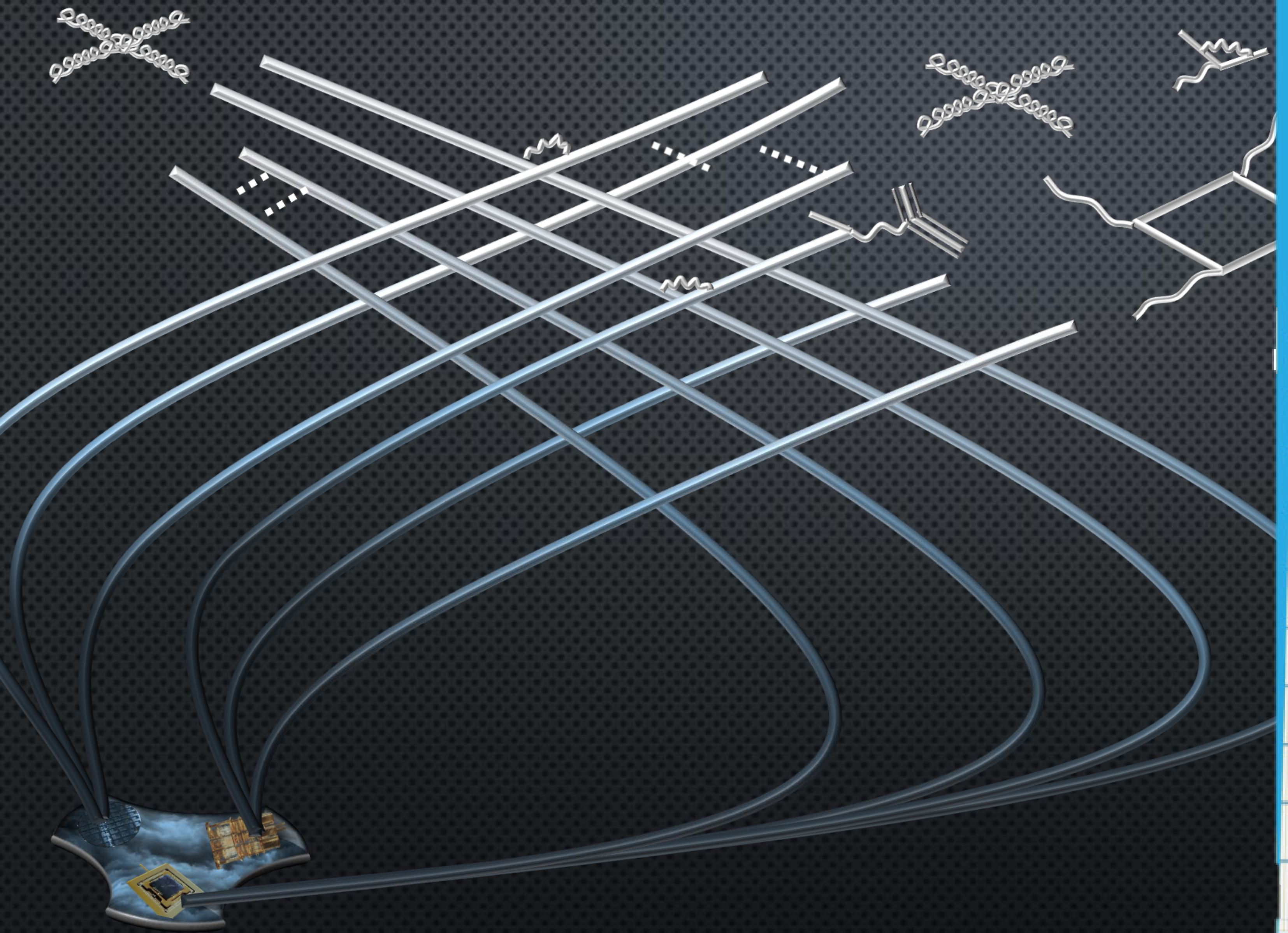
05

Quantum computing for neutrino-nucleus scattering

Alessandro Roggero, Andy C. Y. Li, Joseph Carlson, Rajan Gupta, and Gabriel N. Perdue

Phys. Rev. D **101**, 074038 – Published 27 April 2020

06



Codesign Questions:

Entanglement/Complexity of NP simulations

Hardware-advantageous UV/IR entanglement structure?

Gauge Theories for Protection?

The Line?

Simulations Inform Performance for NP Application?