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C²QA

QIS for pdfs, saturation and non-equilibrium dynamics

2023 IS INITIAL STAGES

20th June 2023

João Barata, BNL and C2QA

Why QIS for Nuclear Physics?

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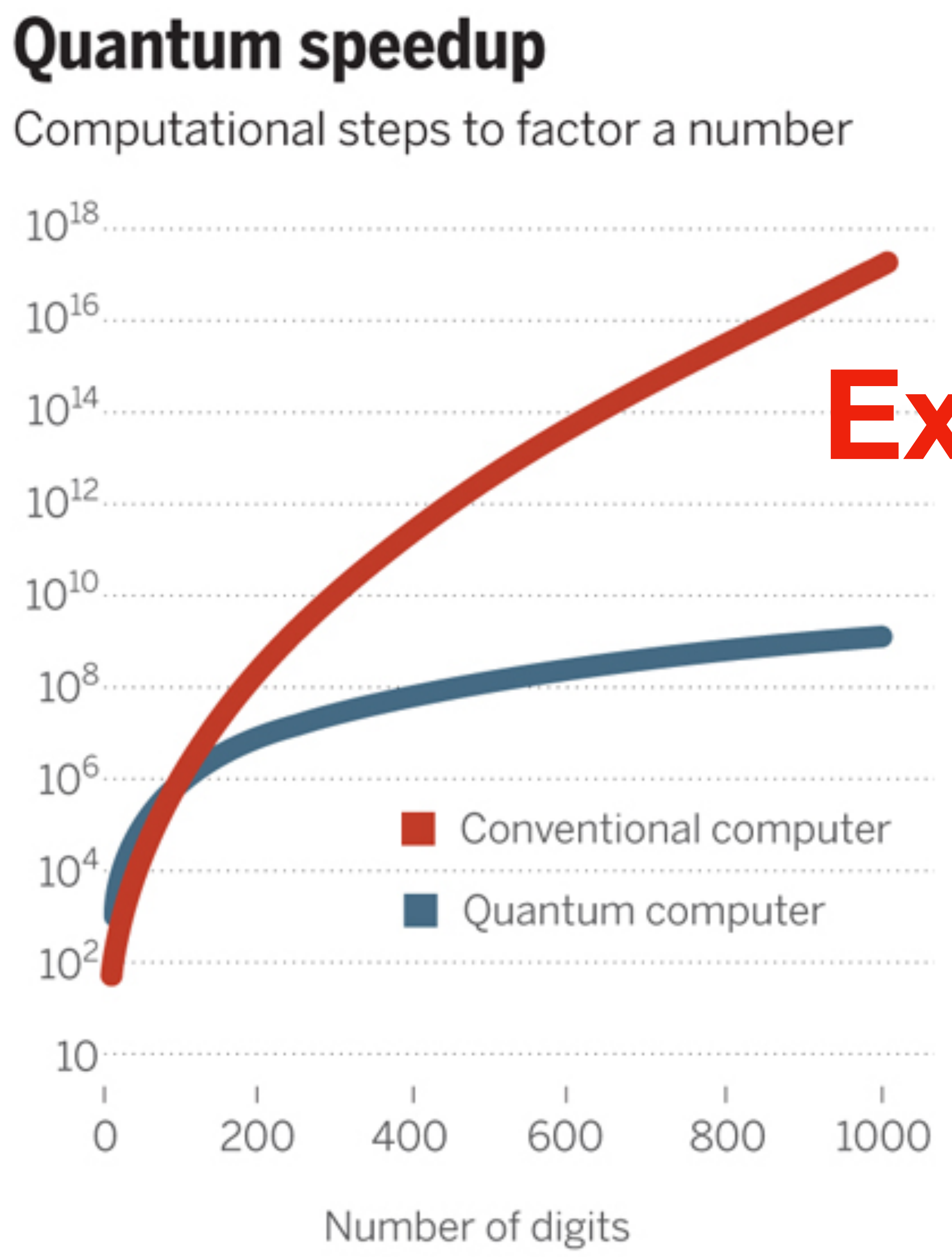
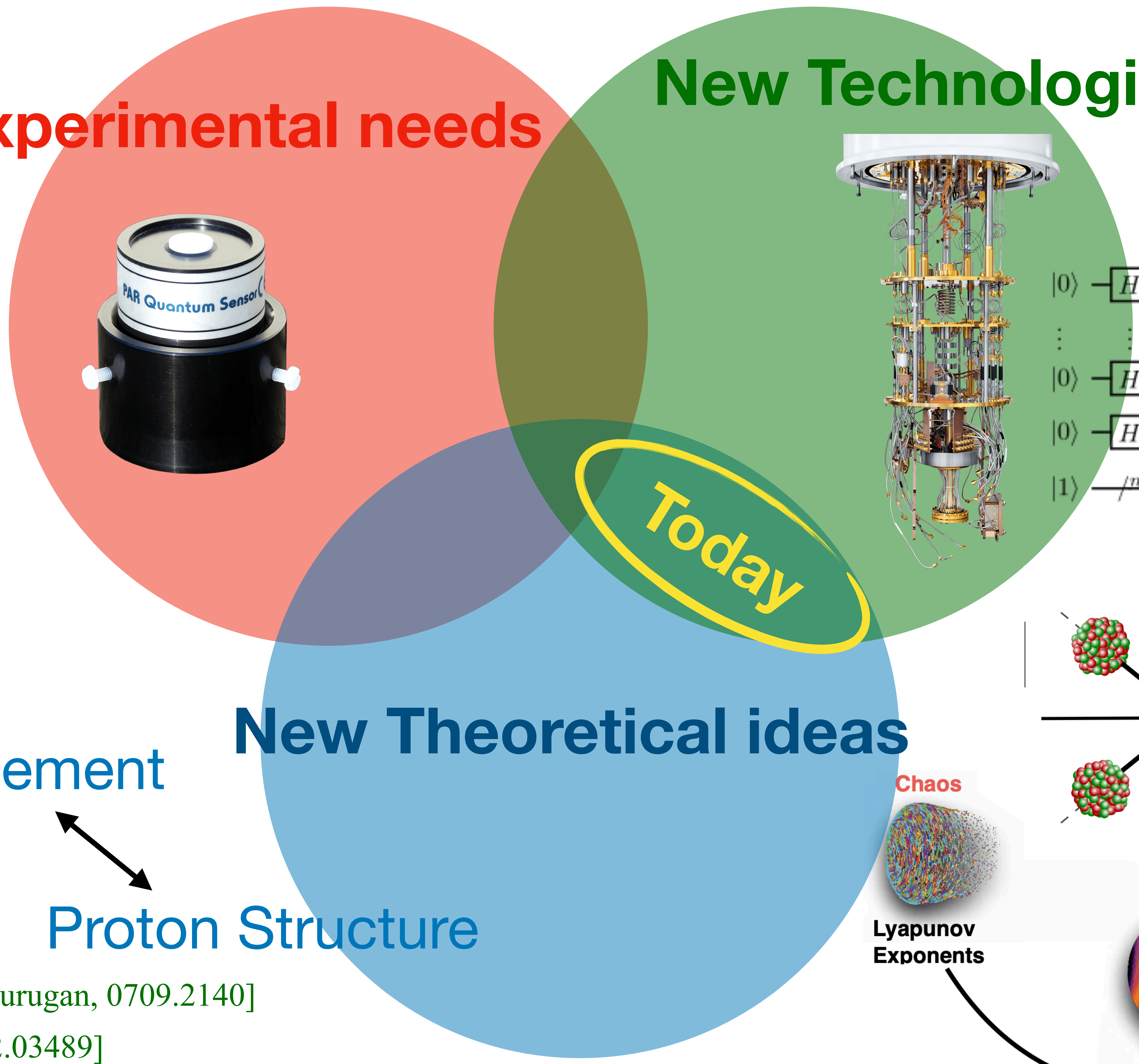
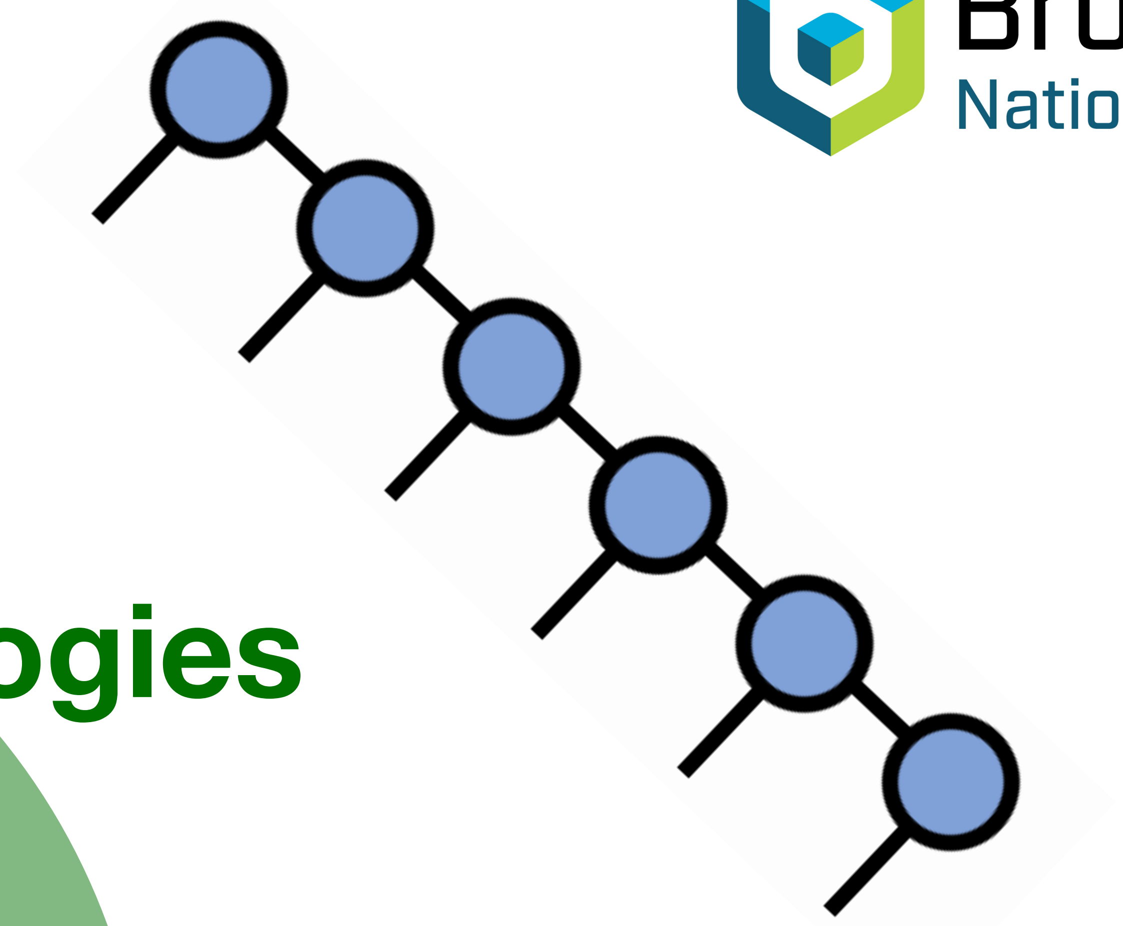
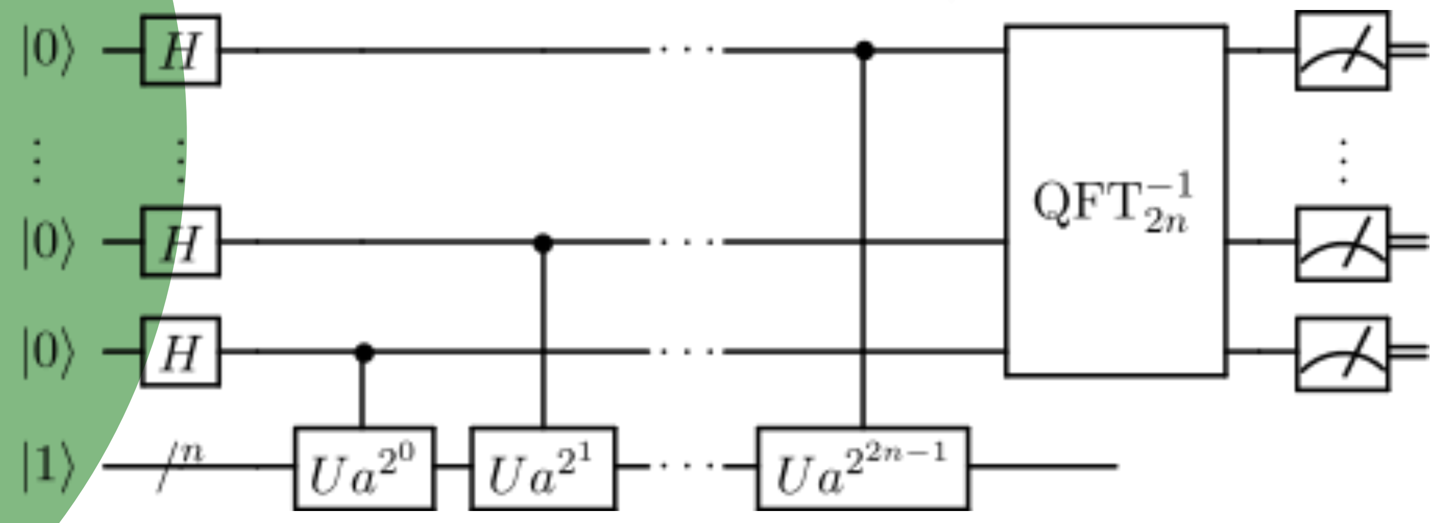








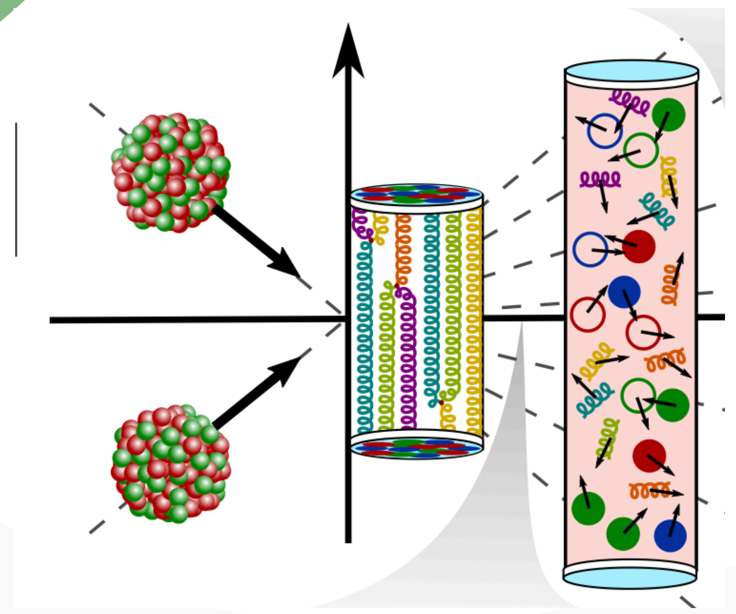
Entanglement

Confinement

Proton Structure

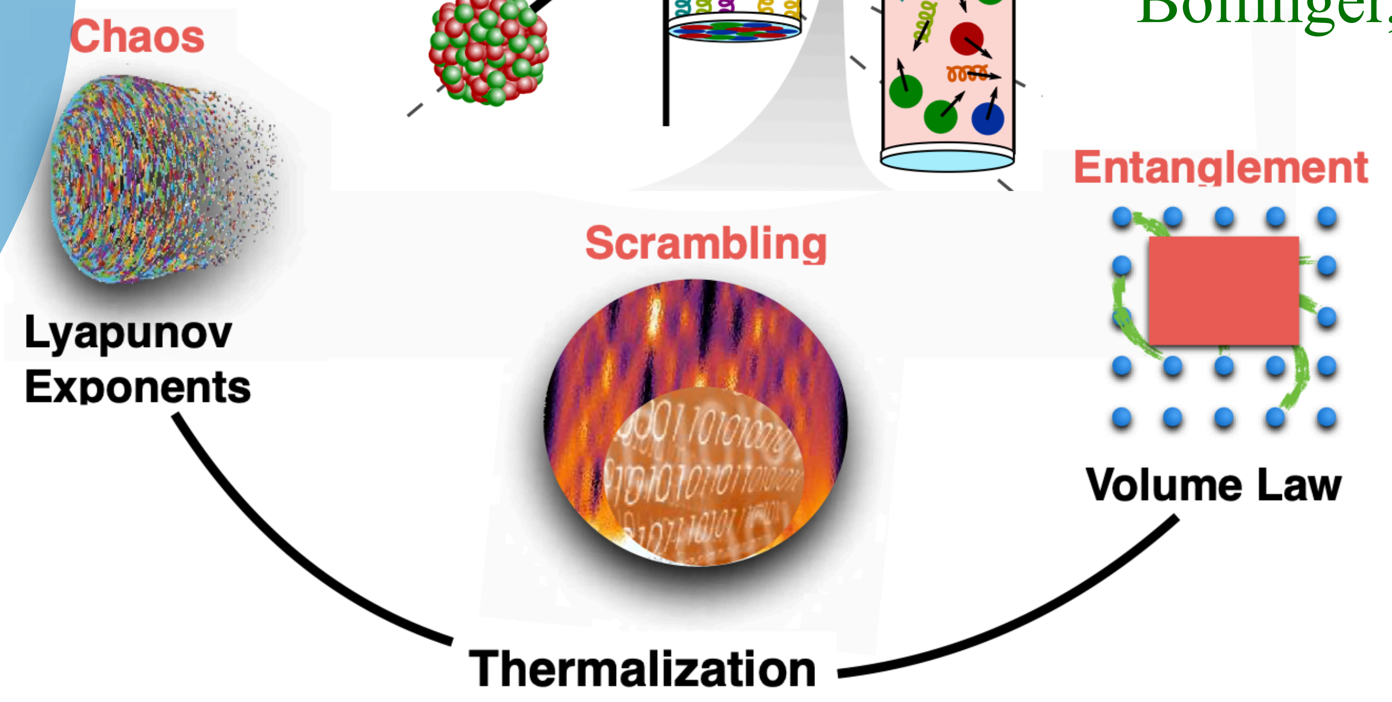
[Klebanov, Kutasov, Murugan, 0709.2140]

[Kharzeev, Levin, 1702.03489]



[Berges et al, 2005.12299]

[Lewis-Swan, Safavi-Naini, Bollinger, Rey, 1808.07134]



Outline

1. New Technologies

2. Applications in experimental HEP

3. Theory and Pheno applications

→ Structure of matter

→ Fragmentation

→ Non-perturbative and out of equilibrium physics

1 New Technologies

[Reviews in back up slides]

Analog quantum simulators

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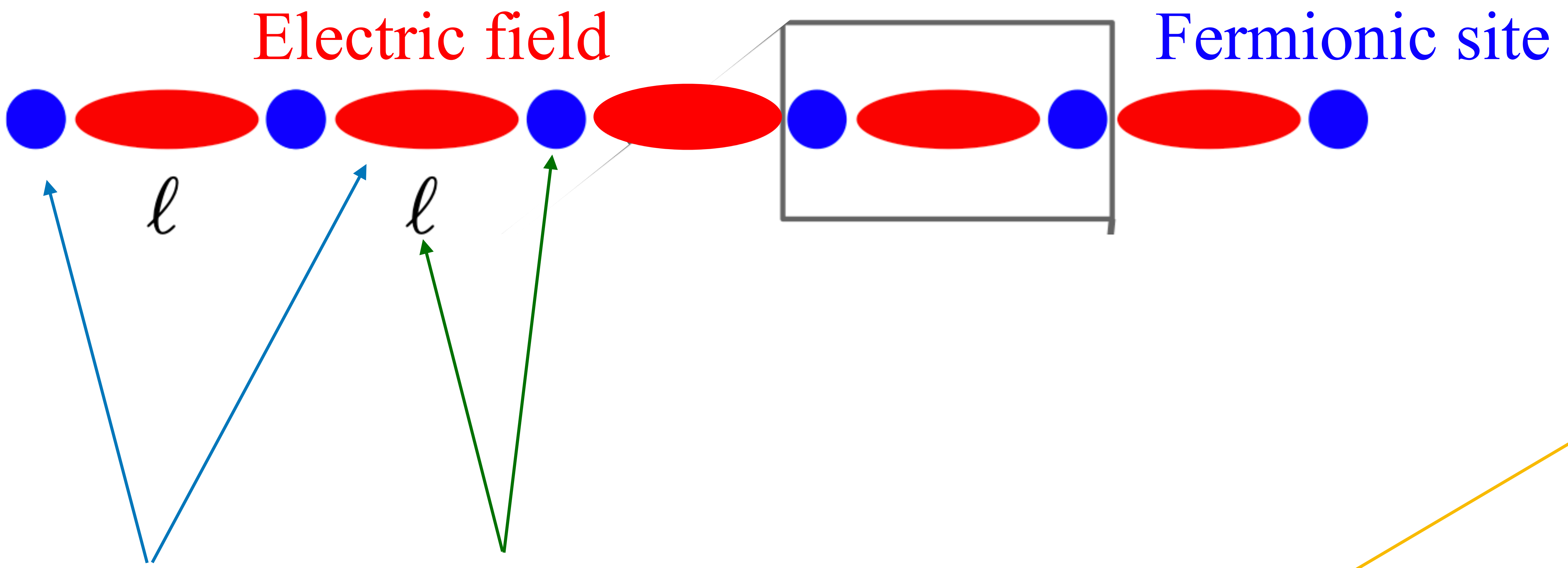
Basic idea: A controllable quantum system that can be engineered to mimic a physical system

An example: 1+1d lattice QED = Quantum Link model with truncated electric field; spin ℓ

QED/QLM



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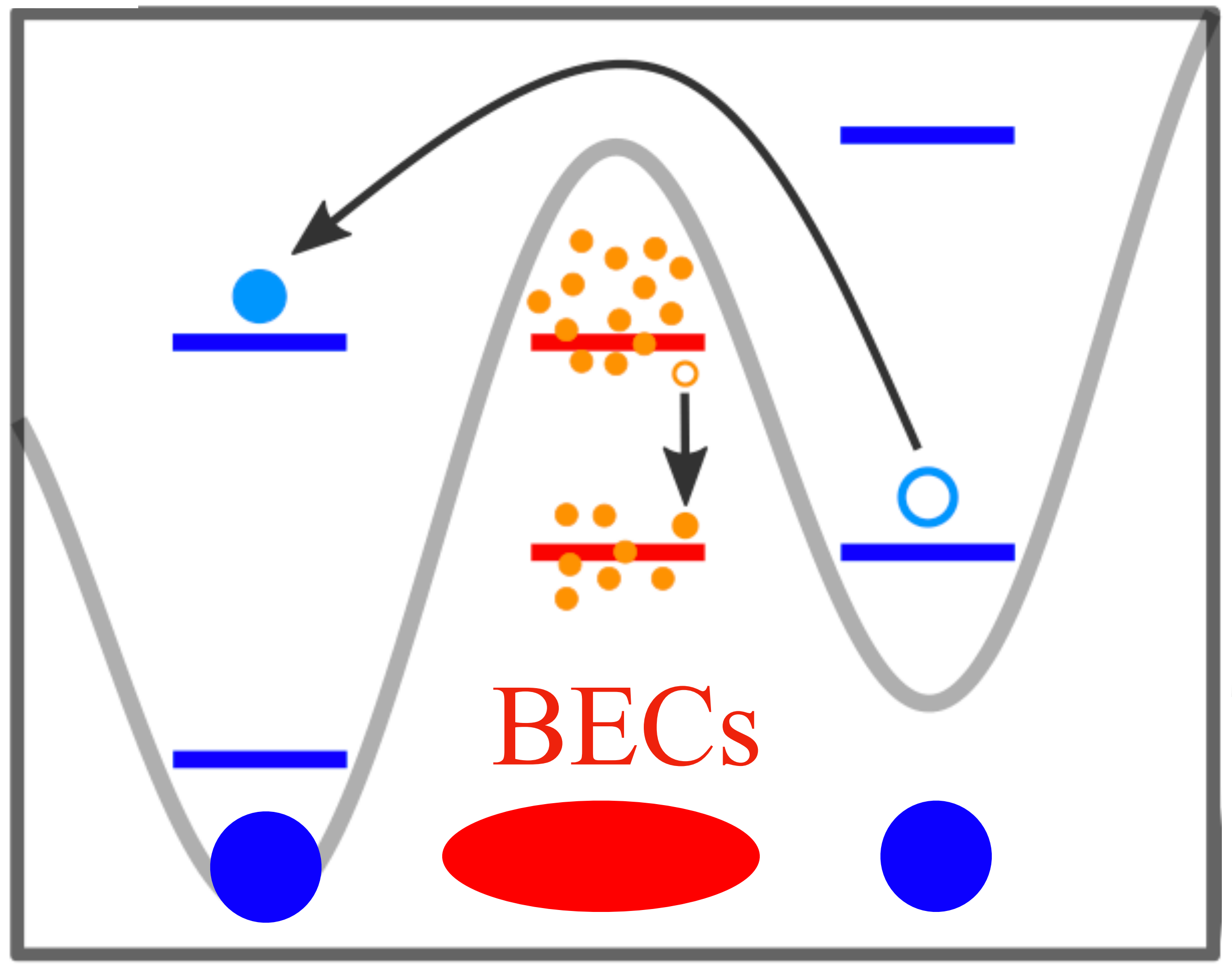
Cold atom Simulator



$$H_{\text{QED}} = H_{\text{QLM}} + \mathcal{O}(1/\ell) = H_{CA}$$

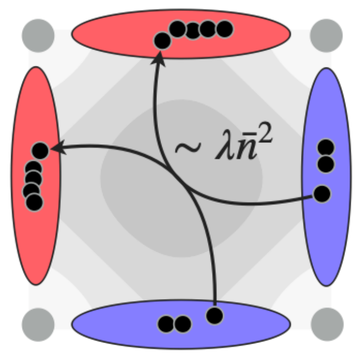
The most successful platform, but:

Non universal approach

Analog

New: 2+1d extensions

[Ott, Zache, Jendrzejewski, Berges, 2012.10432]



Digital quantum computers

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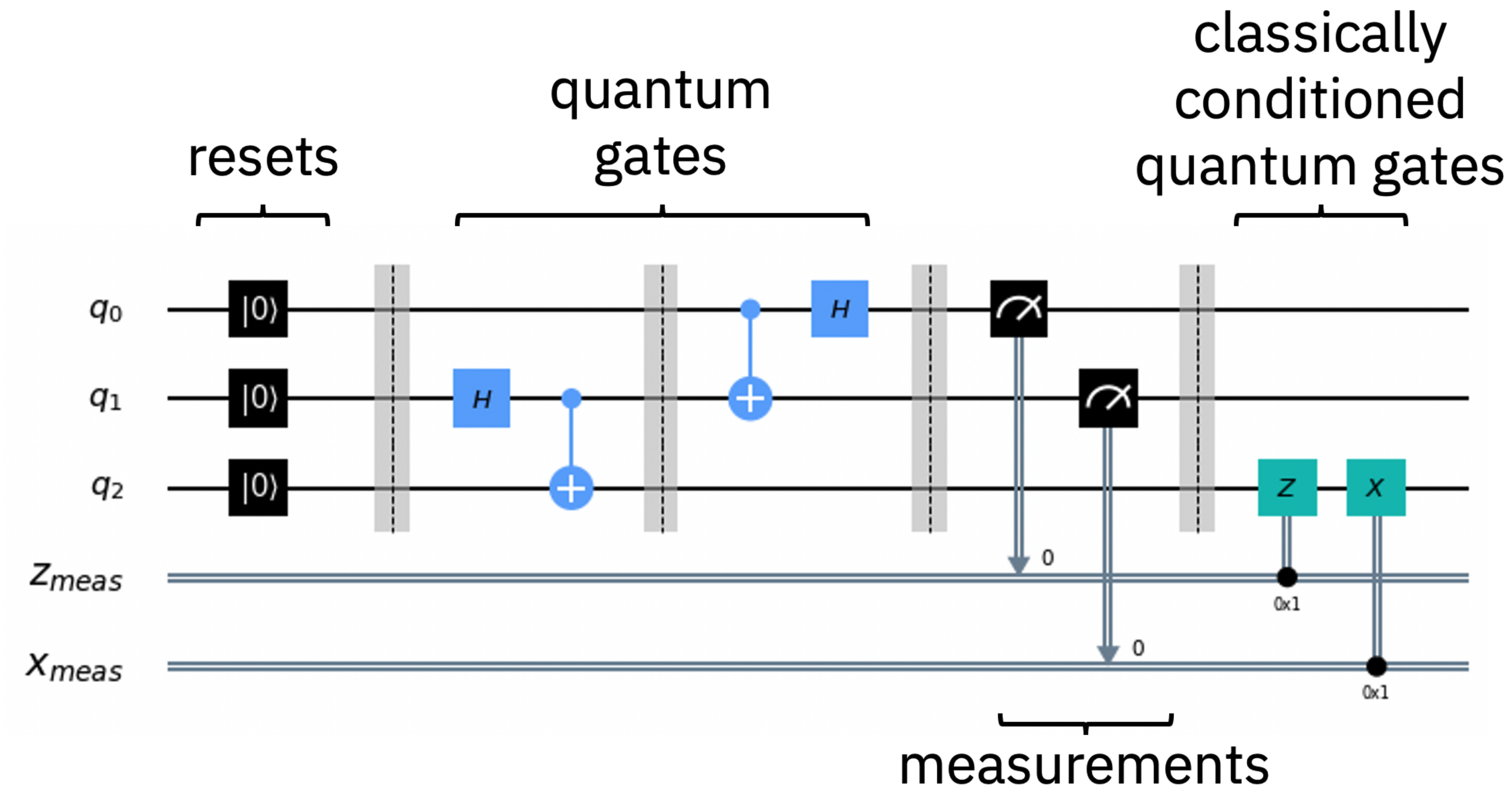
Basic idea: A spin-chain where local operators can be applied

Computer = many qubits (lines) + unitary gates (operators)



$$|\psi\rangle = H^0 O_+^{01} O_+^{12} H^1 |q_0\rangle |q_1\rangle |q_2\rangle$$

Several implementations

Microsoft Quantum Computer

rigetti

IBM Q

IONQ

Conceptually simple, but:

Few qubits

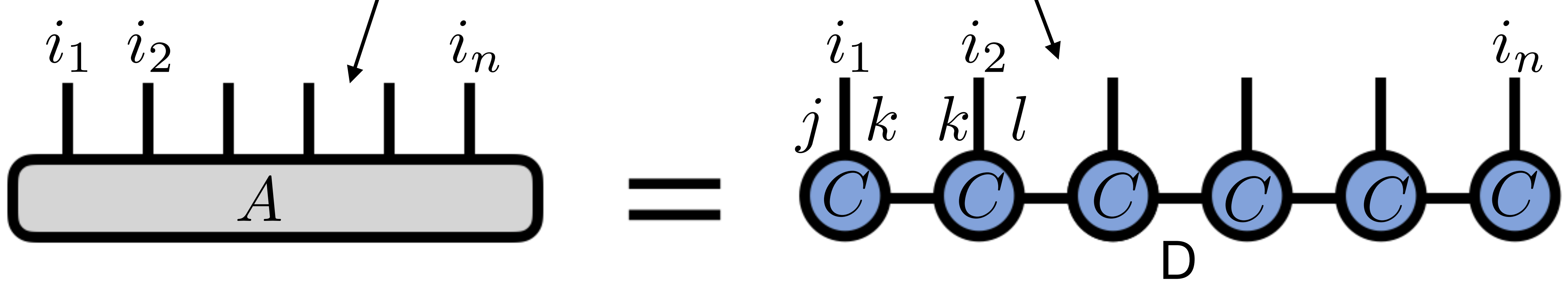
External noise

Tensor Networks (classical)

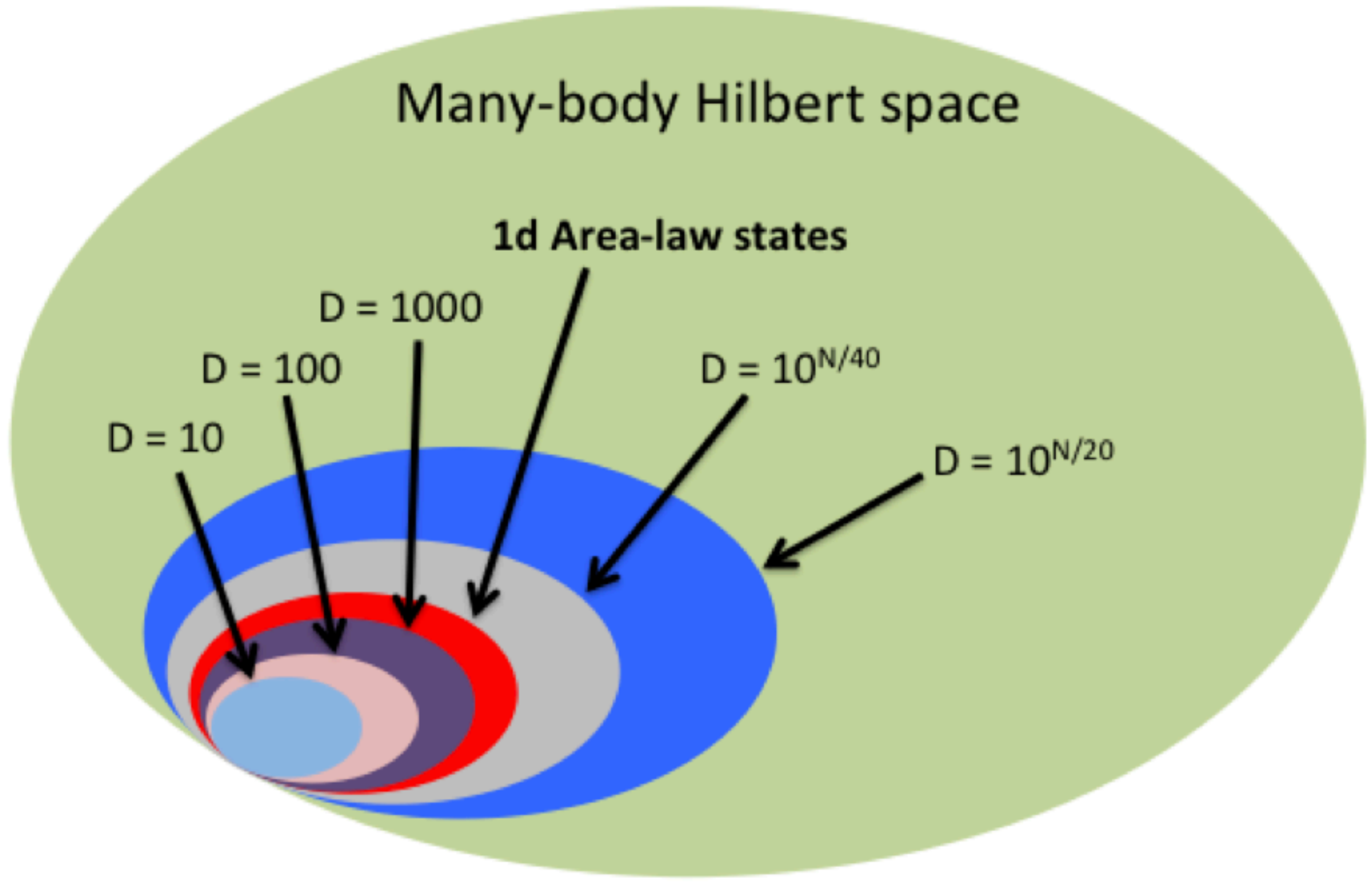
Basic idea: Lowest states of a gapped local Hamiltonian obey the area-law for entanglement entropy
i.e. they are highly constrained by locality

$$|\psi\rangle = \sum_{i_j} A_{i_1 i_2 \cdots i_n} |i_1\rangle |i_2\rangle |i_3\rangle \cdots |i_n\rangle$$

$$A_{i_1 i_2 \cdots i_n} = C_{i_1}^{jk} C_{i_2}^{kl} \cdots$$



$S \sim \log D$



[Wilson] [White]

Very powerful in 1+1d ! Best example: density matrix renormalization group algorithm

Fails when: Long time evolution Near critical points

2 Applications in experimental HEP

QIS for experimental HEP

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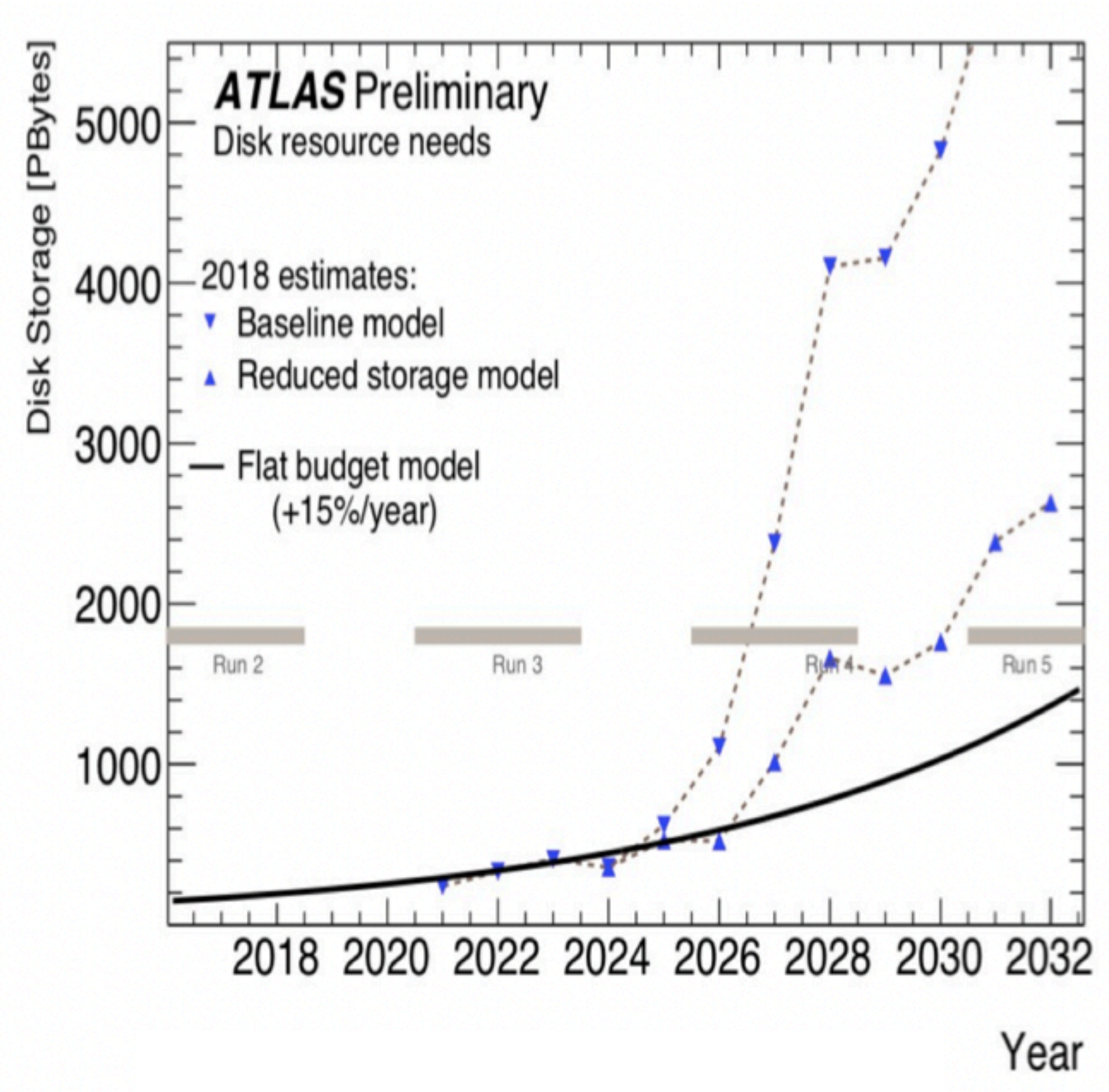
Motivated by large amounts of data…

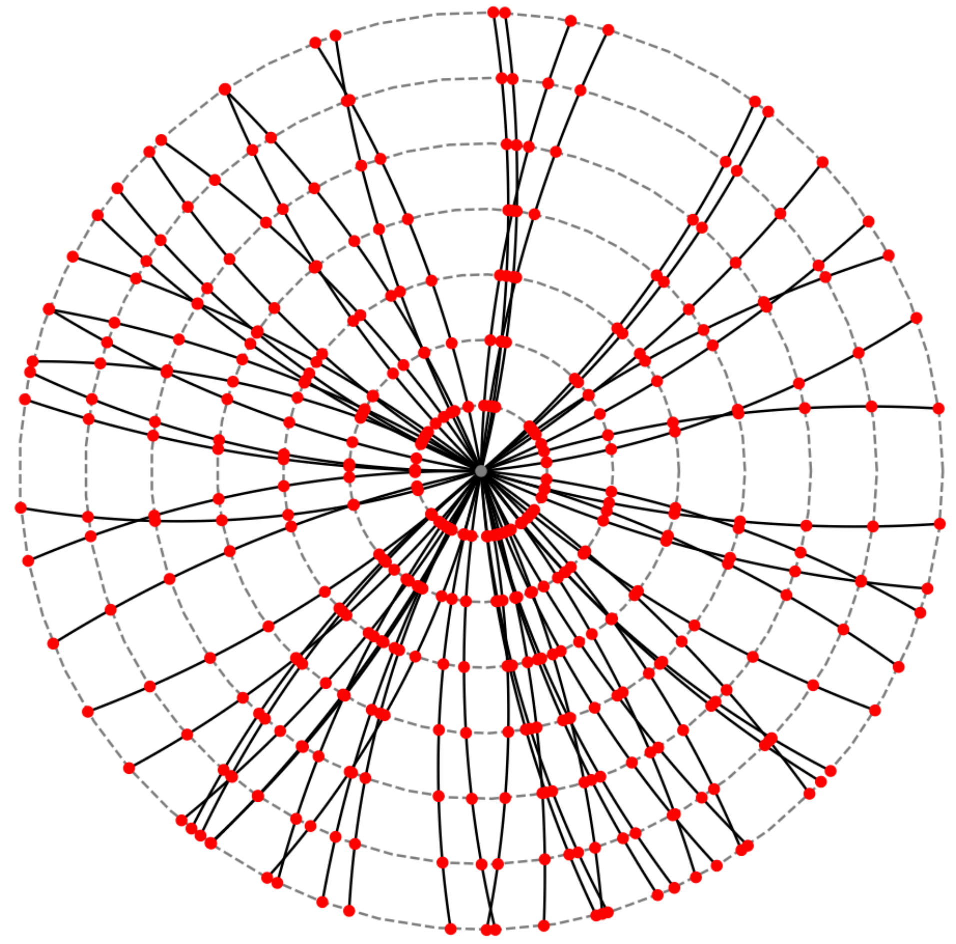


… and optimization tasks

Several applications

Particle tracking
[Zlokapa et al, 1908.04475]
[Magano et al, 2104.11583]

Jet clustering
[Wei, Nail, Harrow, Thaler, 1908.08949]
[Pires, Bargassa, Seixas, Omar, 2101.05618]
[Delgado, Thaler, 2205.02814]



Detector simulation
[Yeon Chang et al, 2101.11132]

Anomaly detection
[Alvi, Bauer, Nachman, 2206.08391]
[Ngairangbam, Spannowsky, Takeuchi, 2112.04958]

Quantum sensing
[Degen, Reinhard, Cappellaro, 1611.02427]

For recent review : [Delgado et al, 2203.08805]

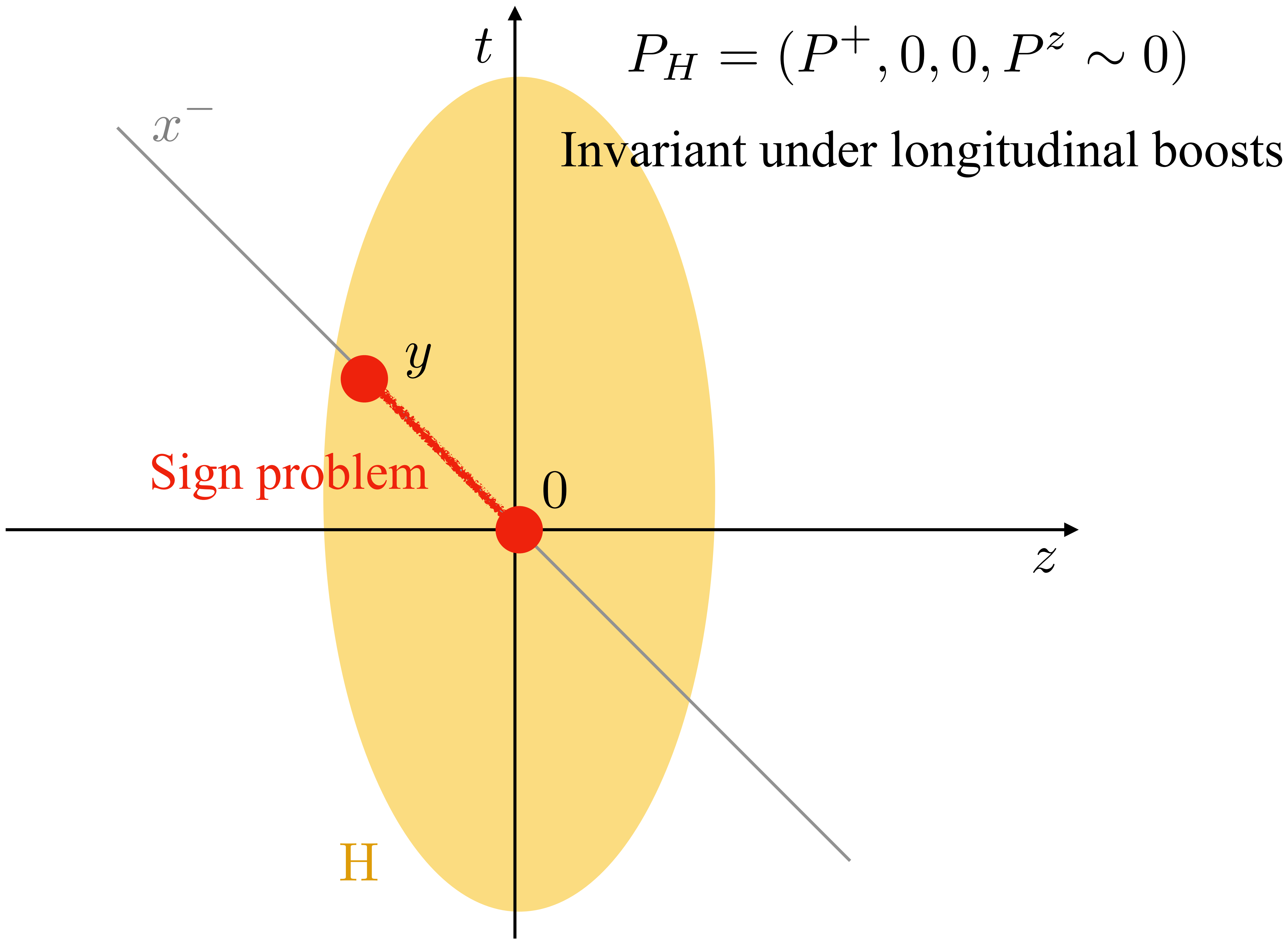
3

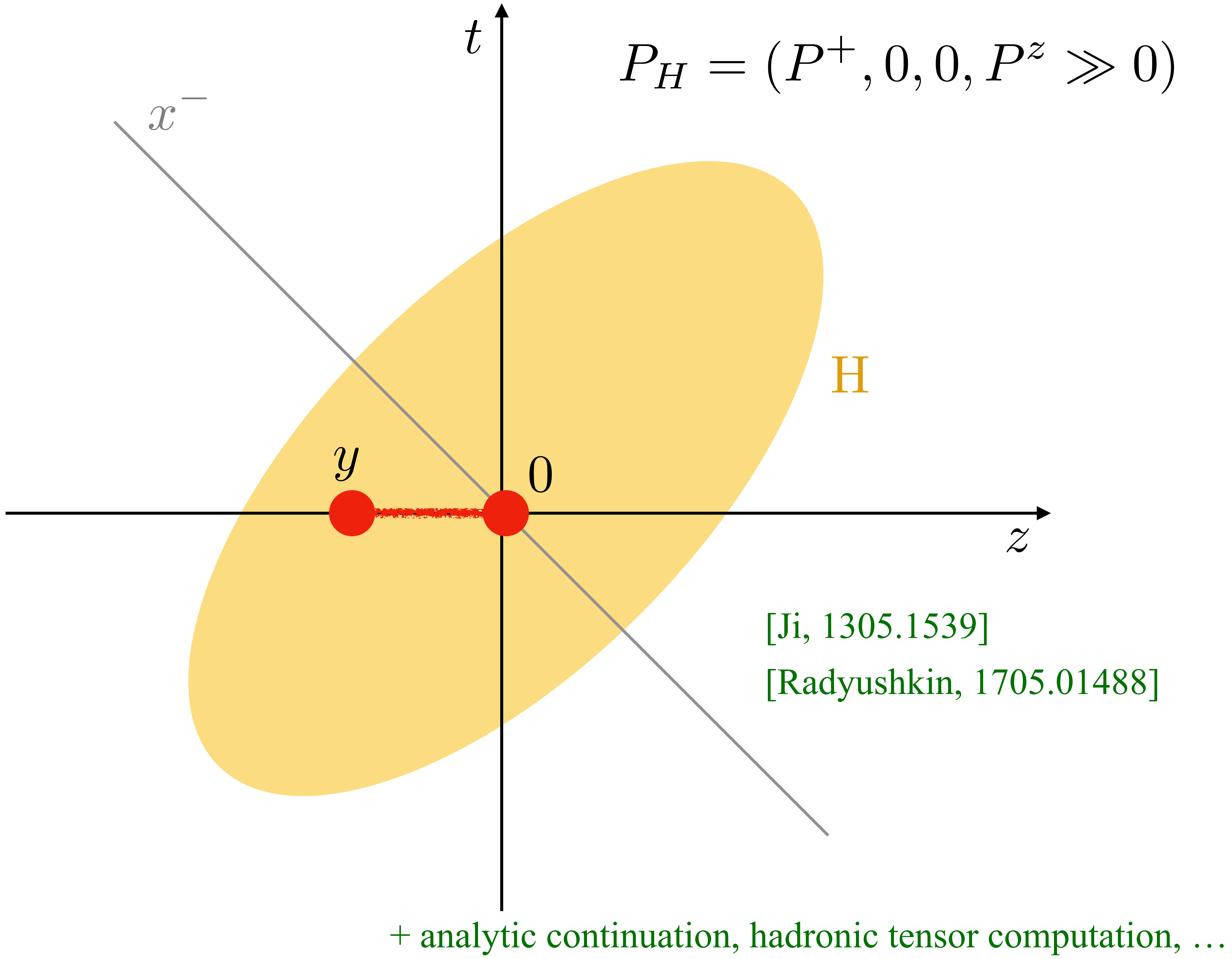
Theory and Pheno applications

Extracting PDFs from quantum computers

$$f(x) = \int dy\, e^{ixP^+ y} \langle \bar{\psi}(y)\gamma^+ W(y)\psi(0)\rangle_{\mathrm{H}}$$

Boost to implement in euclidean lattice





Suitable for quantum calculation

Suitable for classical calculation

Extracting PDFs from quantum computers

Parton Physics on a Quantum Computer [1908.10439]

Henry Lamm,[1,*] Scott Lawrence,[1,†] and Yukari Yamauchi[1,‡]

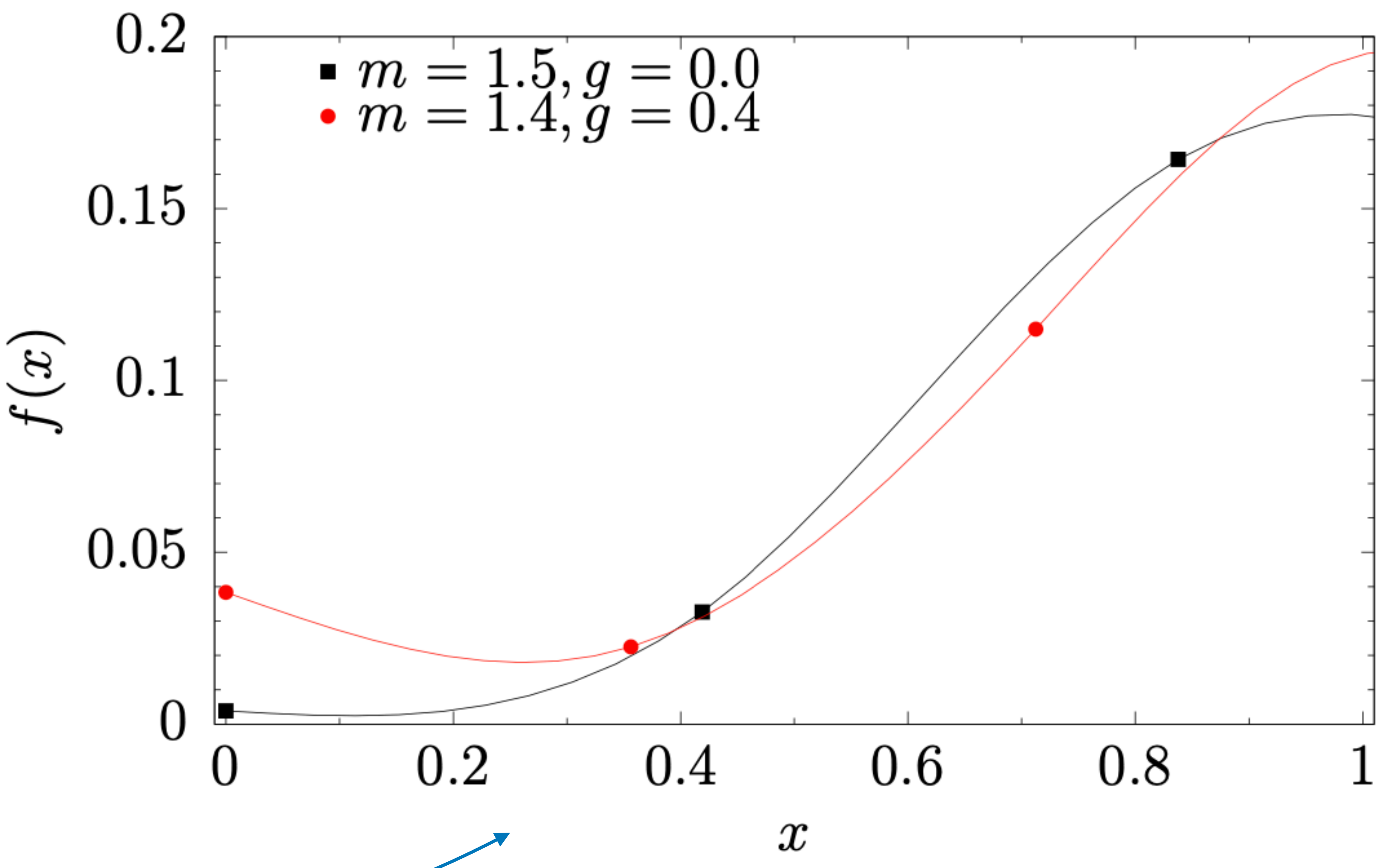
First exploratory calculation of quark distribution in 1+1d Thirring model

$$f(x) = \int dy\, e^{ixP^+ y} \langle \bar{\psi}(y)\gamma^+ W(y)\psi(0)\rangle_{\rm H}$$

(1) Discretization + Kogut-Susskind prescription

[Kogut, Susskind, 1975]

$$f_{\rm stag}(x) = \langle P| \sum_{y,z} e^{ixP(y-z)} \left[\delta^{|y|}_{|z|} + i(-1)^z \delta^{|y|}_{|z+1|}\right] \times e^{iH(y-z)}\chi^\dagger(y)e^{-iH(y-z)}\chi(z)\,|P\rangle$$



(2) Map to spin chain system via Jordan-Wigner transform

Extracting PDFs from quantum computers

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Challenges:

For DLCQ based approaches see:

[Kreshchuk et al, 2002.04016]

[Qian et al, 2112.01927]

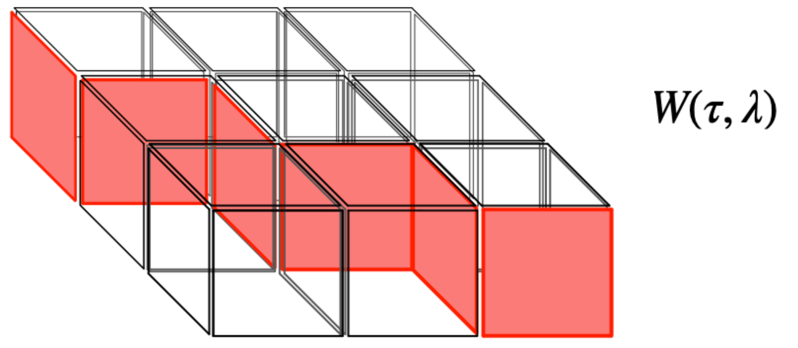
Including Wilson lines :

Compute hadronic tensor (no Wilson lines) [Lamm, Lawrence, Yamauchi, 1903.08807]

[Echevarria, Egusquia, Rico, Schnell, 2011.01275]

Several strategies for measuring Wilson loops, mesonic strings, …

[Zohar, Cirac, Reznik, 1208.4299] [Brennen, 1512.06565] [Zohar, 1911.11156]



$W(\tau, \lambda) = W_{C_1} W_{\tau_1} W_{C_2} W_{\tau_2} \cdots W_{C_k} W_{\tau_k} \cdots$

Target state preparation : Hard and generic problem

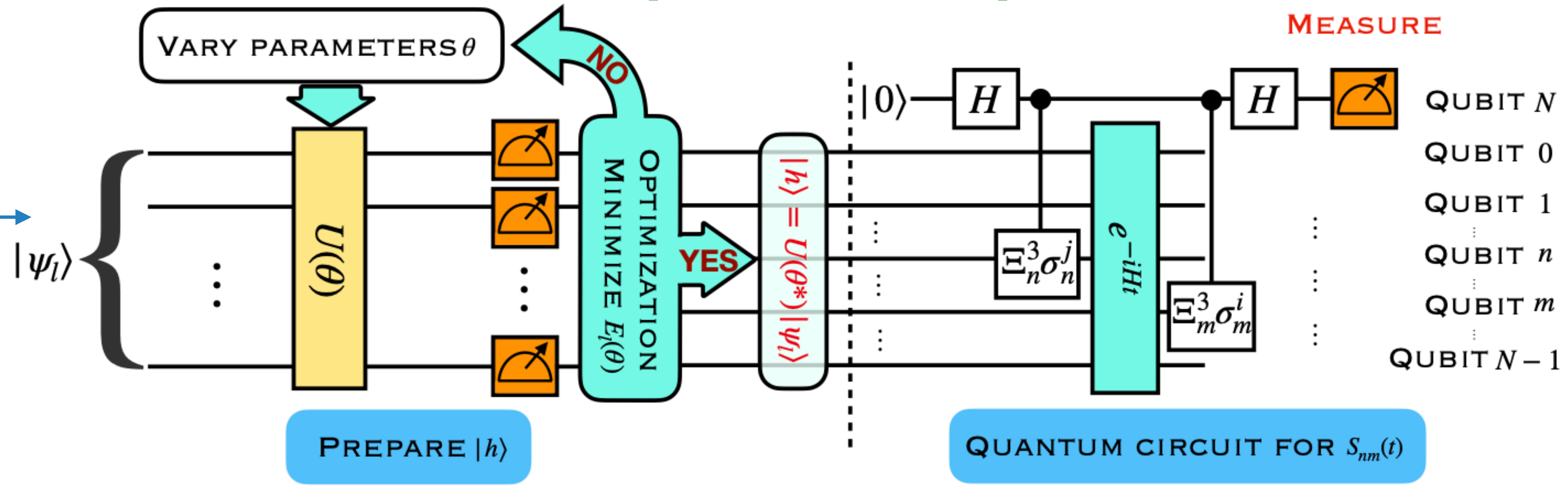
[Li et al, 2106.03865]

Exact Diagonalization [1908.10439]

Variational approaches (VQE)

Tensor Networks

Adiabatic state preparation



Hadronic tensor calculation

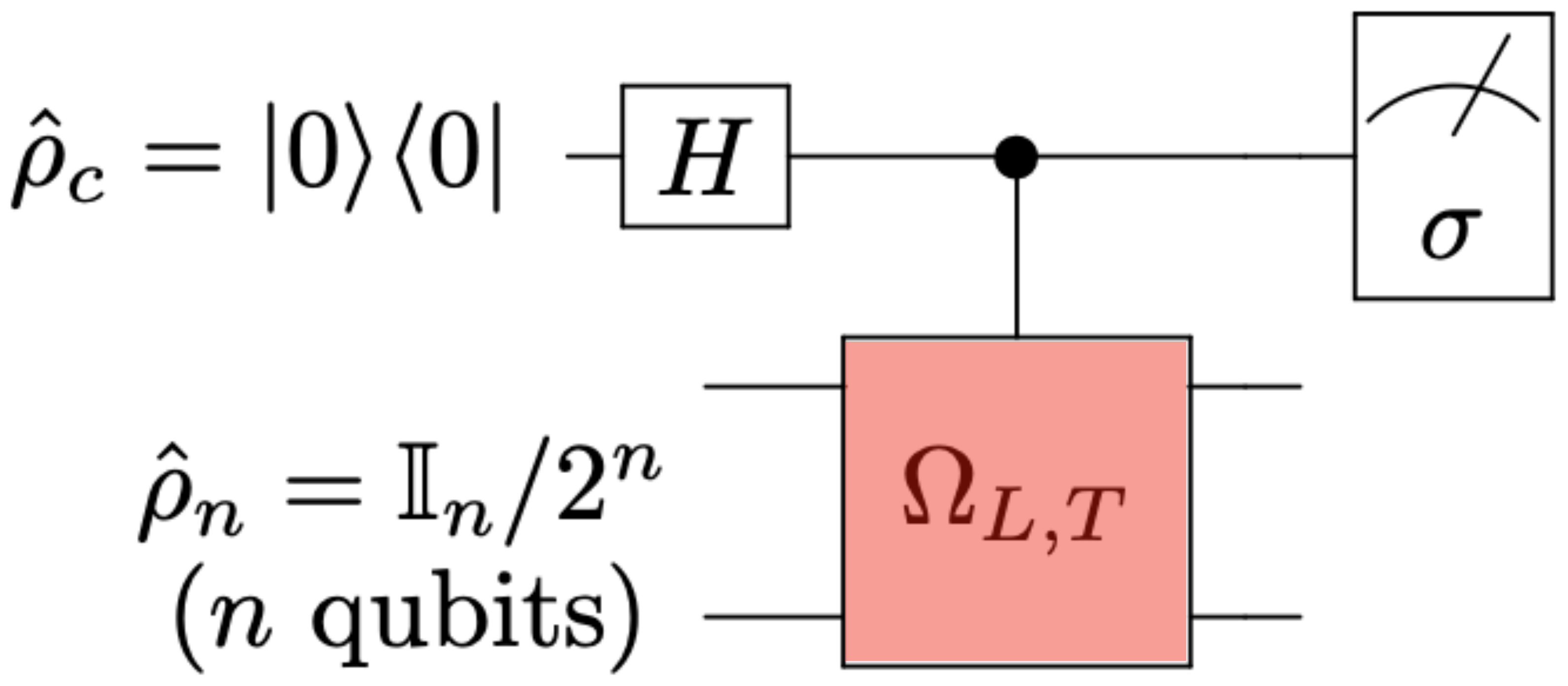
Deeply inelastic scattering structure functions on a hybrid quantum computer [1908.07051]

Niklas Mueller,[1,*] Andrey Tarasov,[1,2,3,†] and Raju Venugopalan[1,‡]

Worldline formulation for QED (QCD) using CGC EFT

$$F_2(q,P) = \frac{\sigma Q^2}{2\pi e^2}\int [\mathcal{D}\rho] W[\rho] \int_{x_\perp}\int_z \sum_{L,T;\,f} |\Psi^f_{L,T}(z,x_\perp)|^2 \times D_\rho(x_\perp)\, i \int d^2\theta \langle -\theta | [\Omega_{L,T}(z,x_\perp)] | \theta \rangle$$

easy to compute using standard methods — easy to compute in Qcomputer



Worldline formulation reduces problem to simple trace

Quantum computers to leverage PDF Fits

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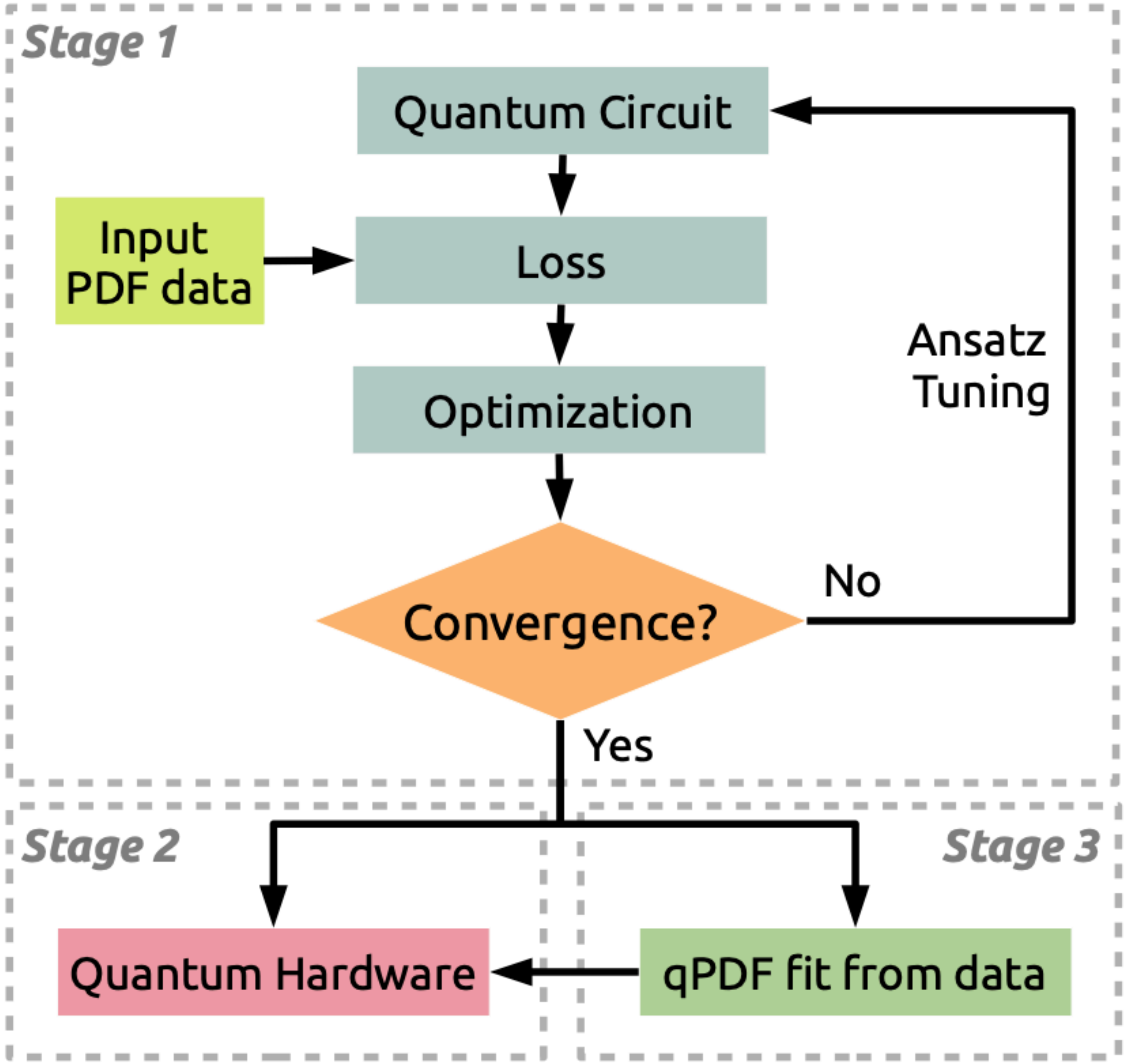
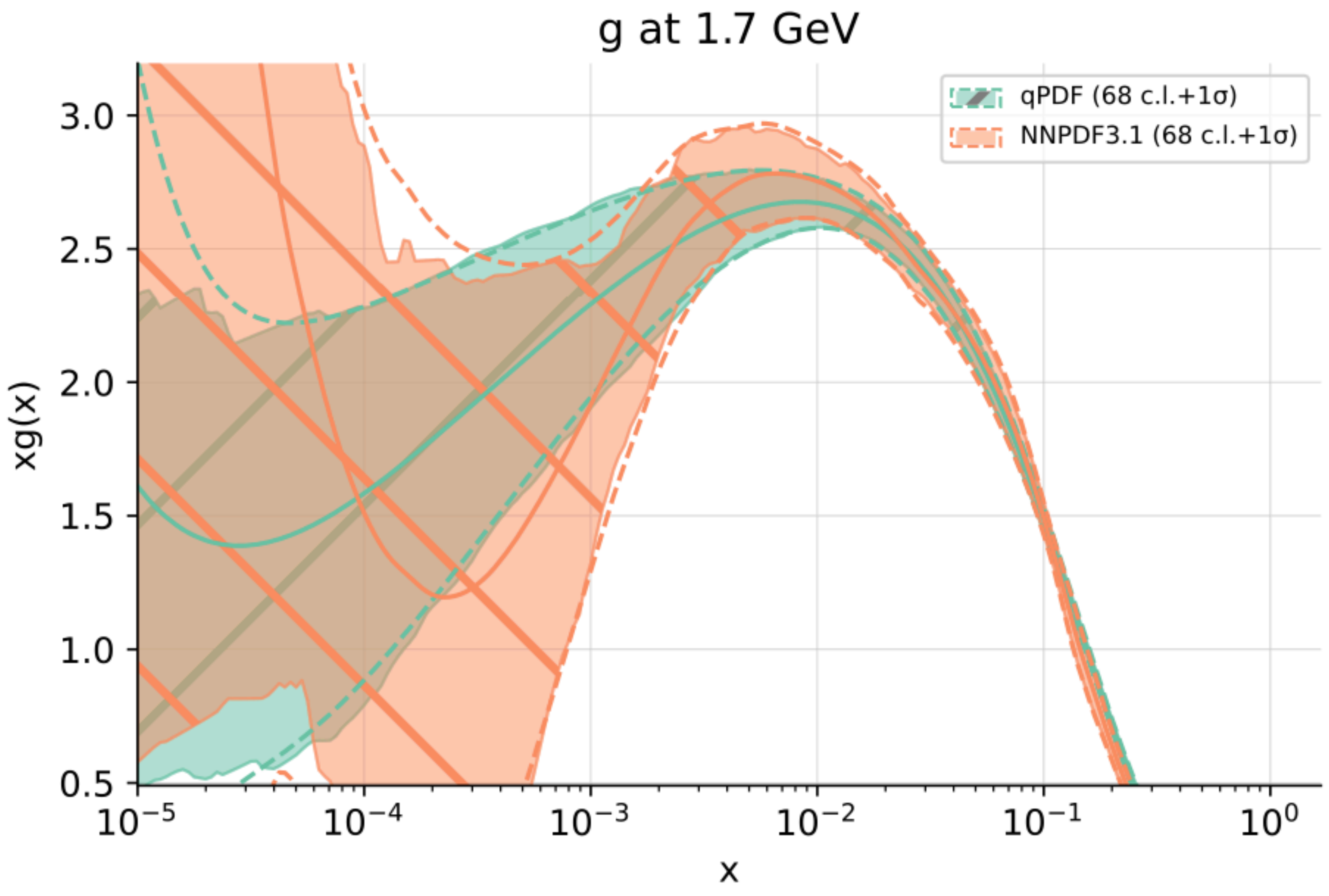
Determining the proton content with a quantum computer [2011.13934]

Adrián Pérez-Salinas,[1,2] Juan Cruz-Martinez,[3] Abdulla A. Alhajri,[4] and Stefano Carrazza[3,5,4]

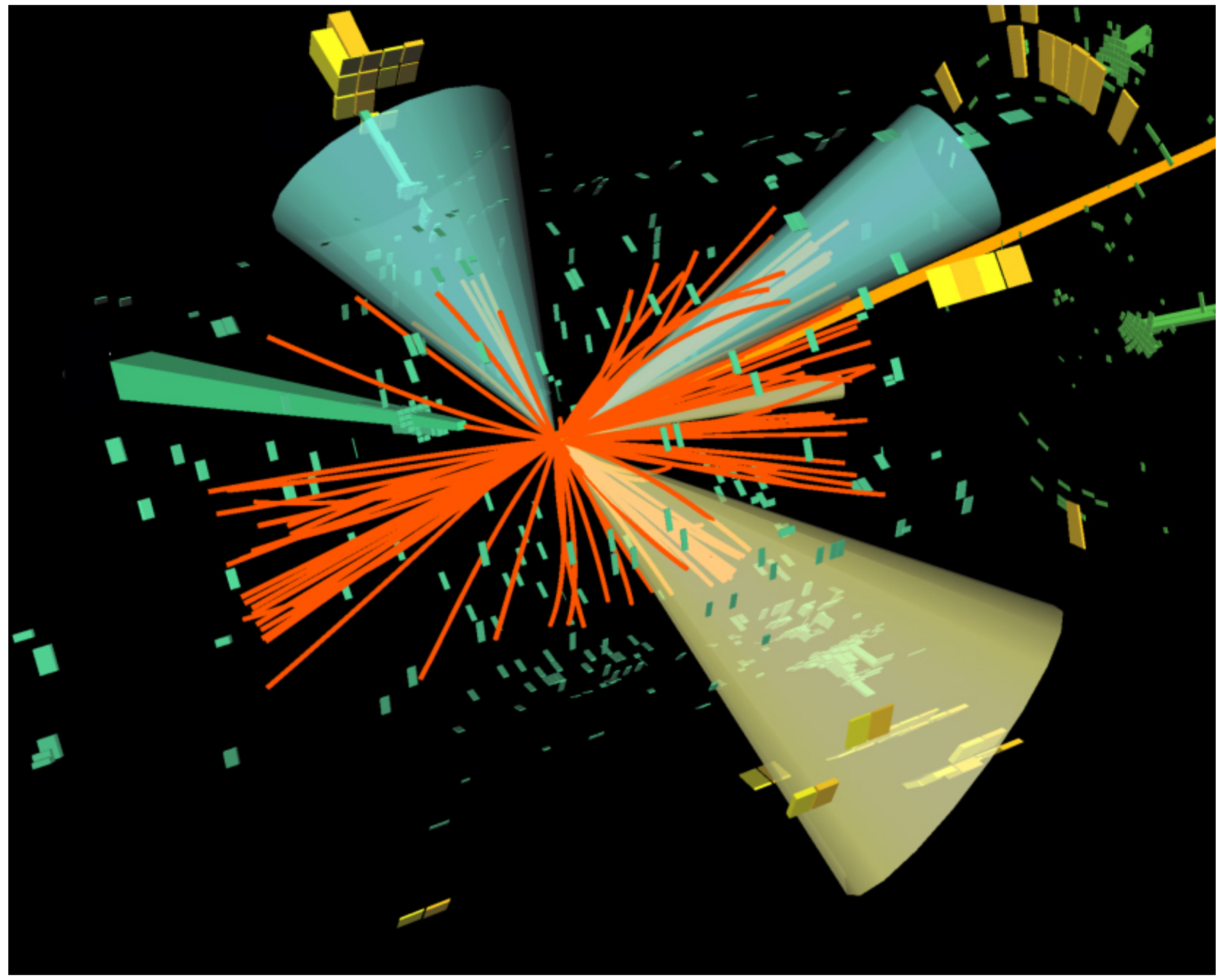
qPDF Workflow VQE style approach





A master algorithm for scattering

[1111.3633] [1404.7115] [1112.4833]



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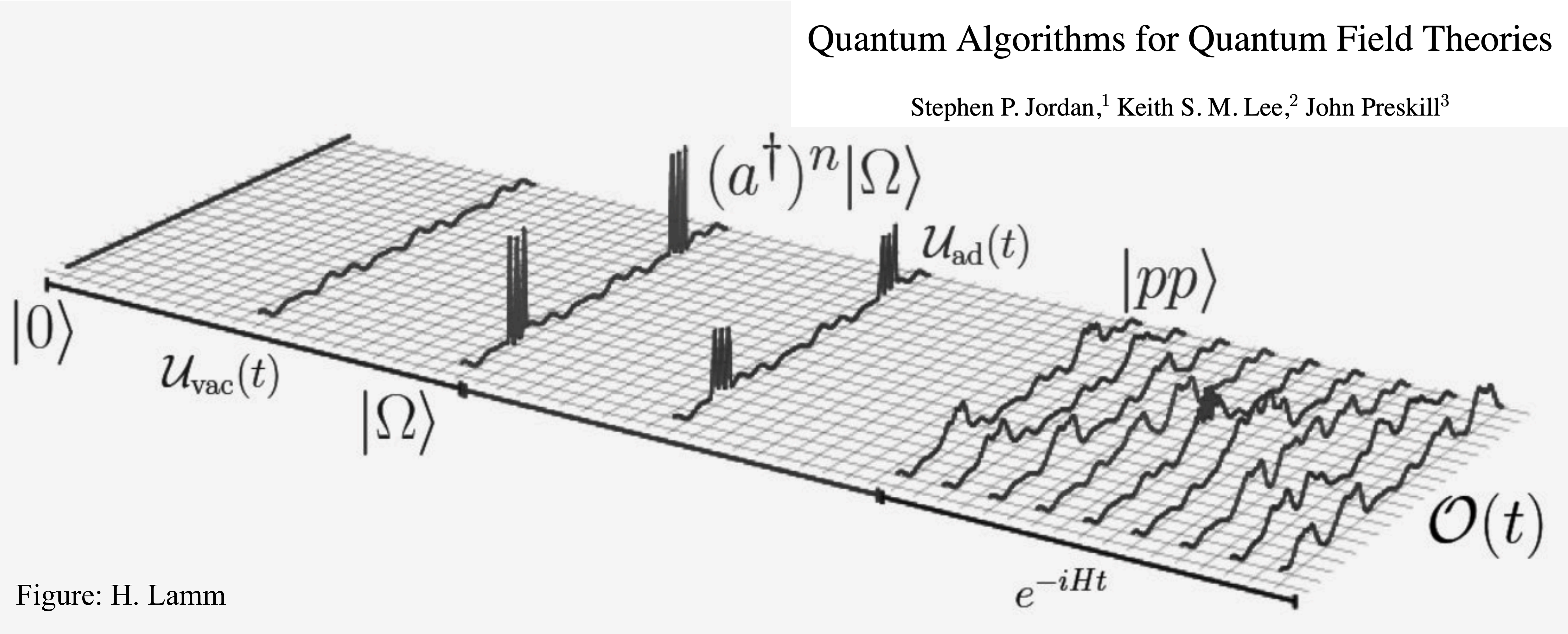


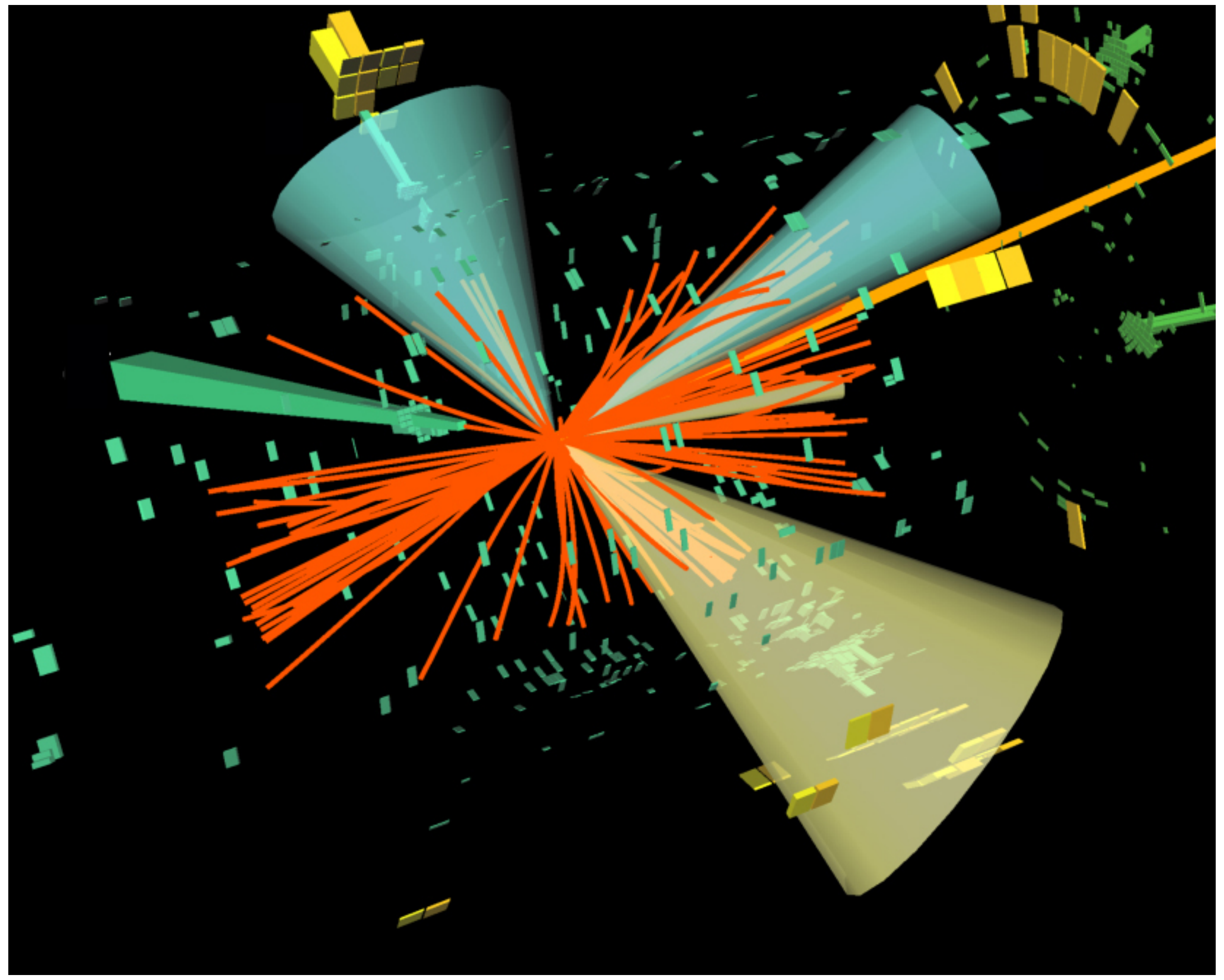
Figure: H. Lamm

Other formulations for scalar theories
[Yeter-Aydeniz et al, 1811.12332]
[Kloc, Savage, 1808.10378]
[Kreshchuk et al, 2002.04016]
[JB, Mueller, Tarasov, Venugopalan, 2012.00020]

⟶ Fundamentally hard problem: physics from MeV to TeV !

⟶ Not guaranteed quantum methods can solve it efficiently

Divide and conquer



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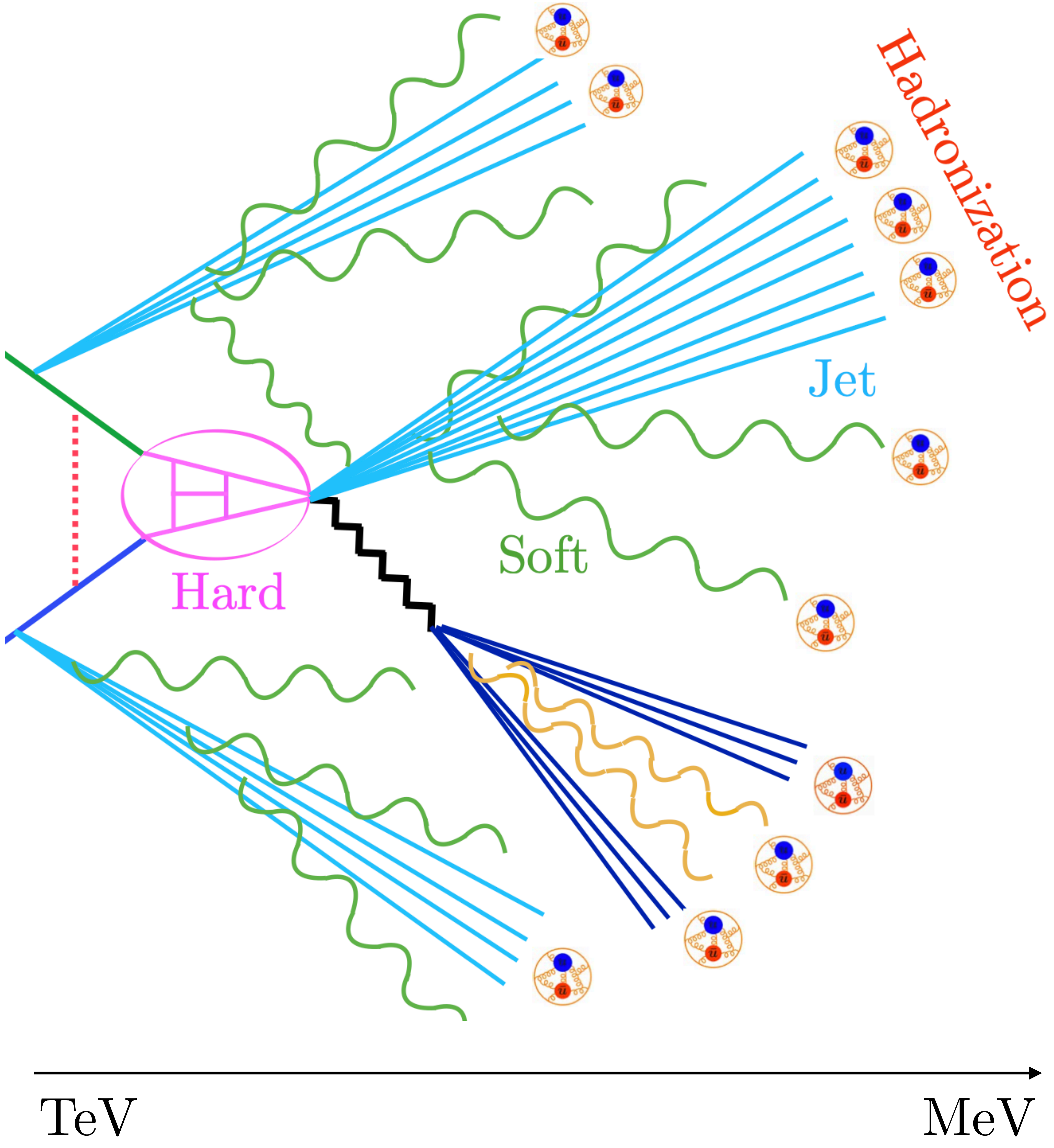

Quantum computers for parton showers

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[1904.03196]

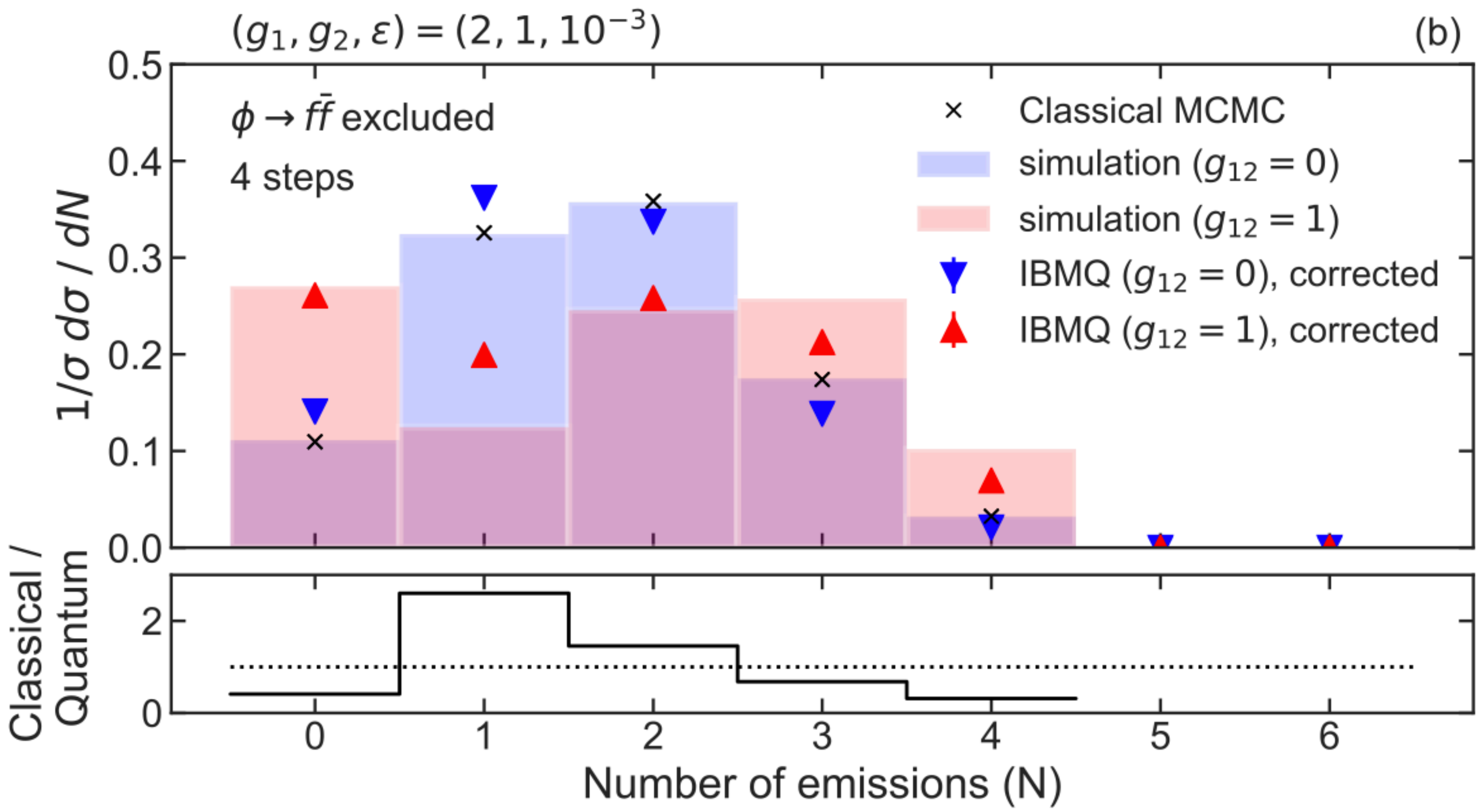
A quantum algorithm for high energy physics simulations

Benjamin Nachman,* Davide Provasoli,† and Christian W. Bauer‡
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Wibe A. de Jong§

Consider theory with non-diagonal flavor operator

$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2 + g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi$$



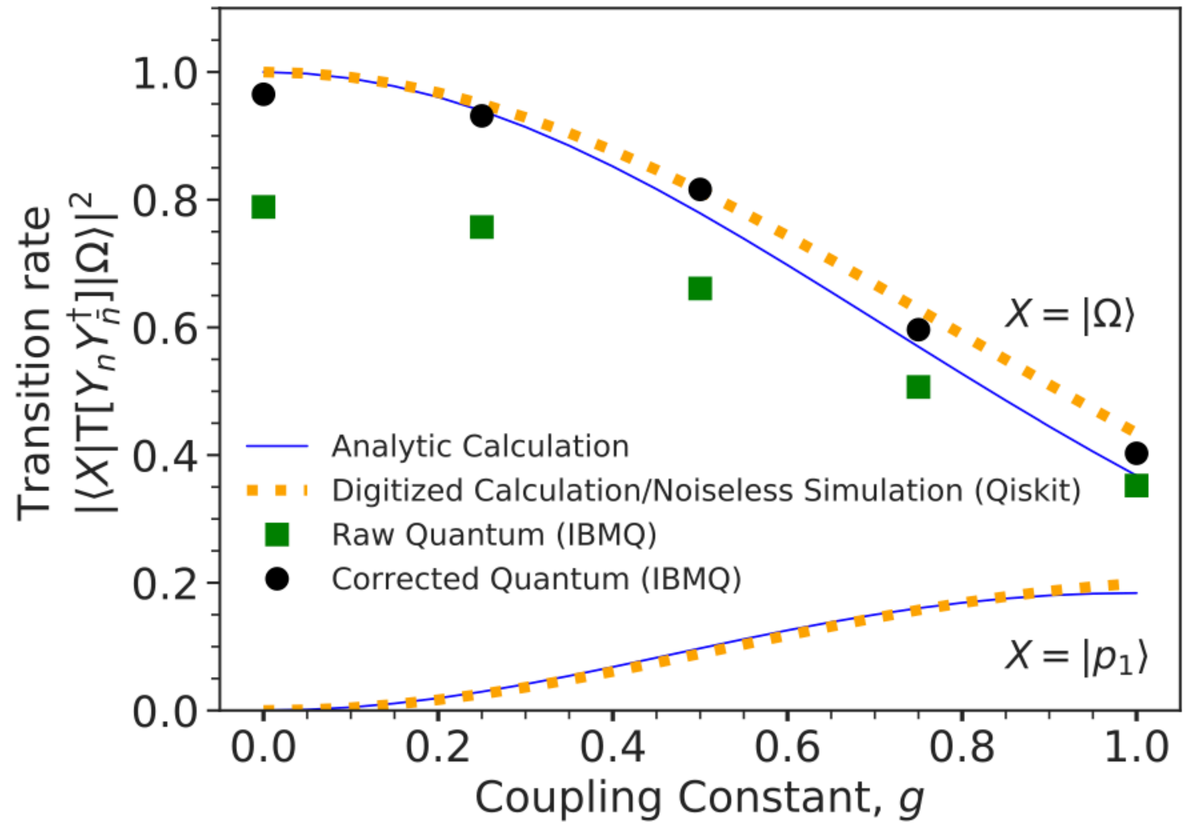
[2102.05044]

Simulating collider physics on quantum computers using effective field theories

Christian W. Bauer* and Benjamin Nachman† Marat Freytsis‡

$$\sigma = H \otimes J_1 \otimes \cdots \otimes J_n \otimes S$$

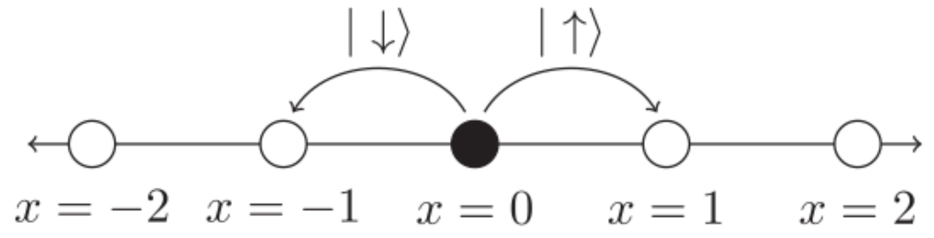
$$\langle X|\mathrm{T}[Y_n\, Y_{\bar{n}}^\dagger]|\Omega\rangle$$

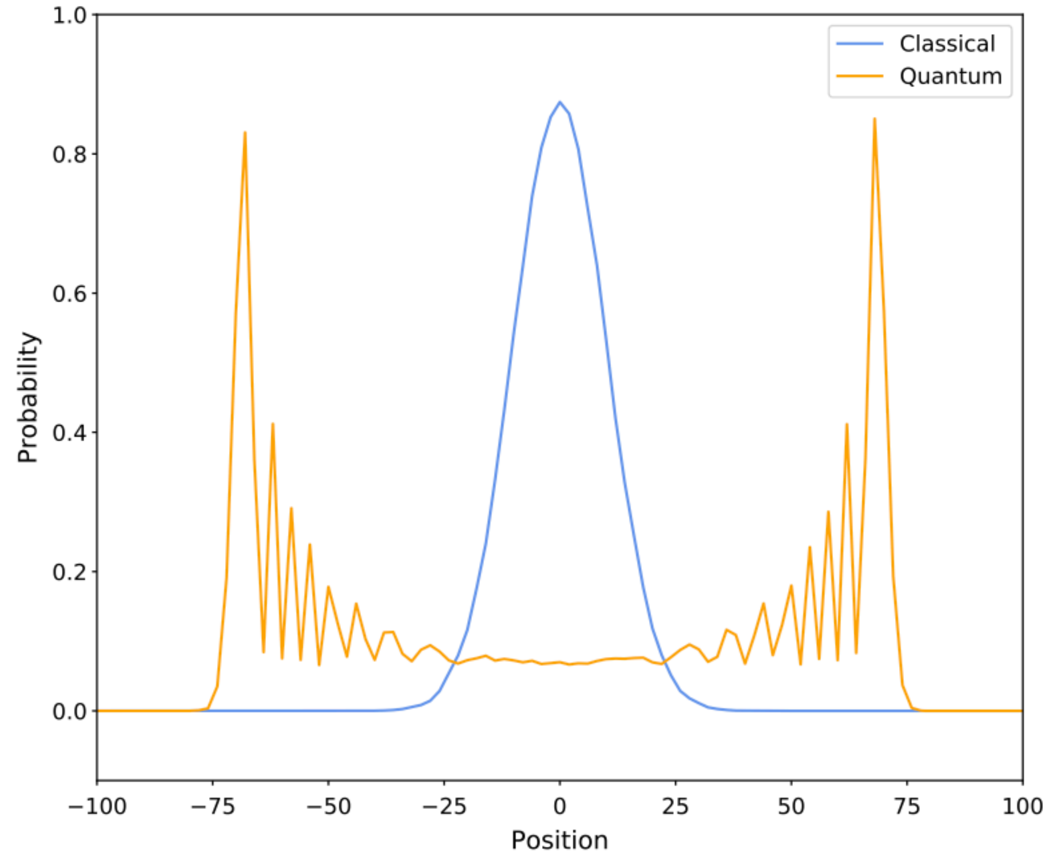


[2109.13975]

Quantum walk approach to simulating parton showers

Khadeejah Bepari,[a] Sarah Malik,[b] Michael Spannowsky[a] and Simon Williams[c]





QIS for probes of nuclear matter

[2010.03571] [2106.08394]

Quantum simulation of open quantum systems in heavy-ion collisions

Wibe A. de Jong,[1,*] Mekena Metcalf,[1,†] James Mulligan,[2,3,‡]
Mateusz Płoskoń,[2,§] Felix Ringer,[2,¶] and Xiaojun Yao[4,**]

Open quantum systems formulation for quarkonia, jets, …

[Blaizot, Escobedo, 1711.10812, 1803.07996]
[Akamatsu, 2009.10559]

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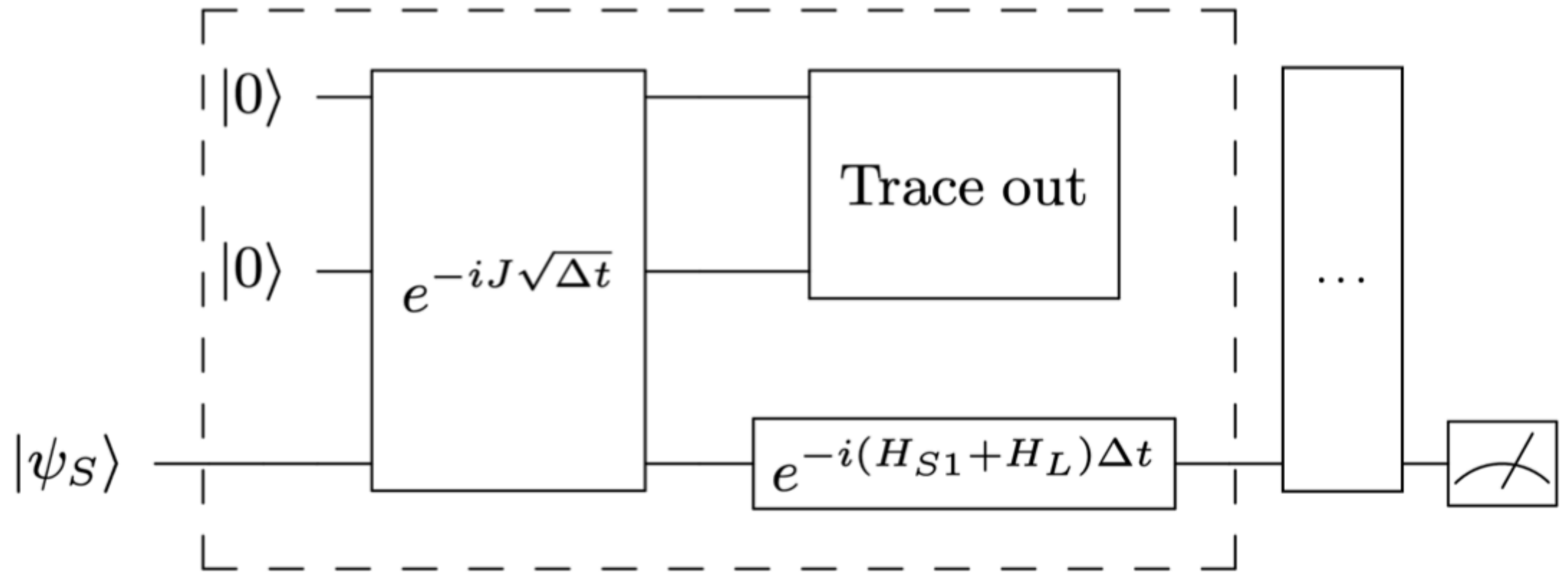
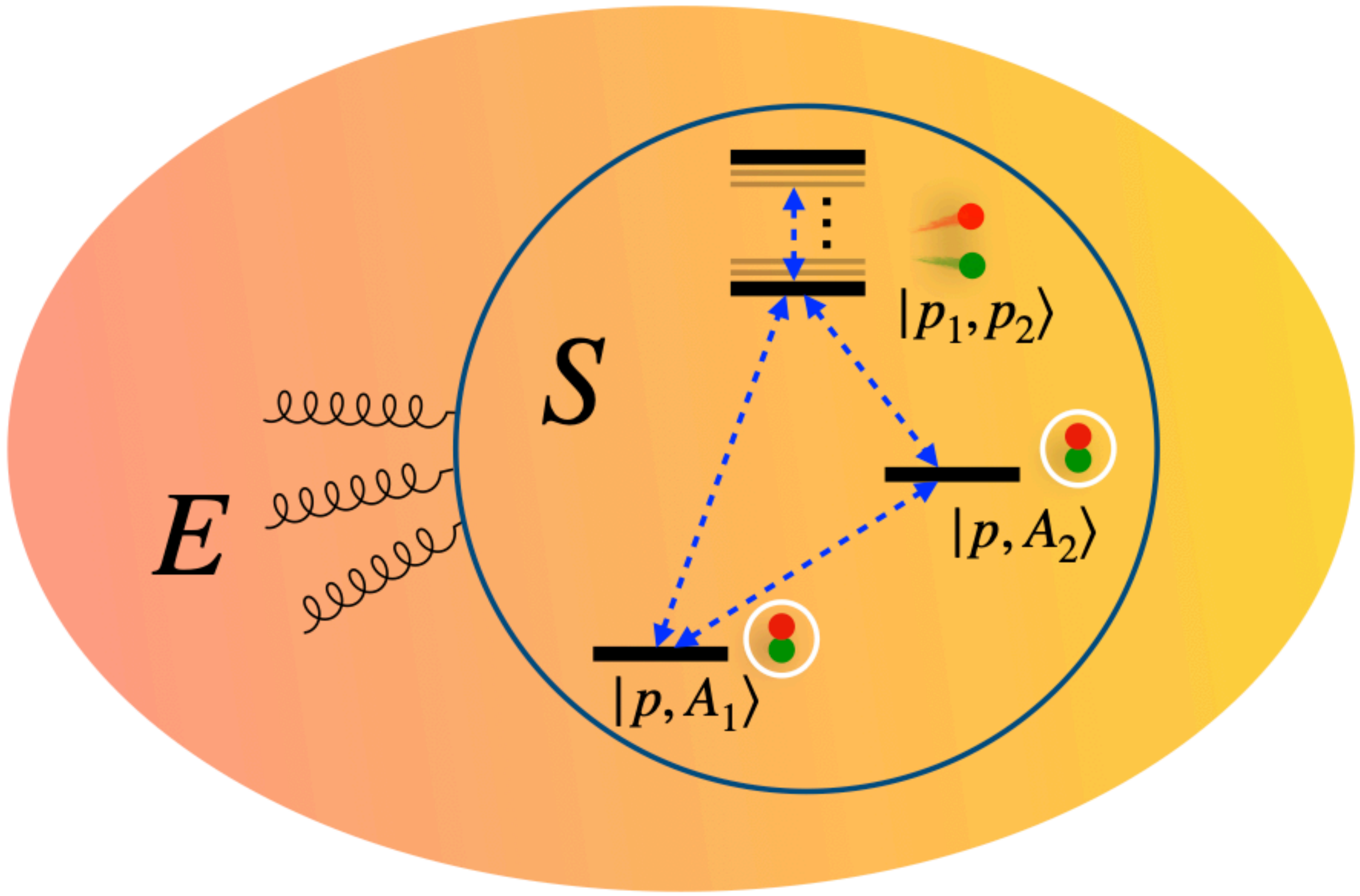
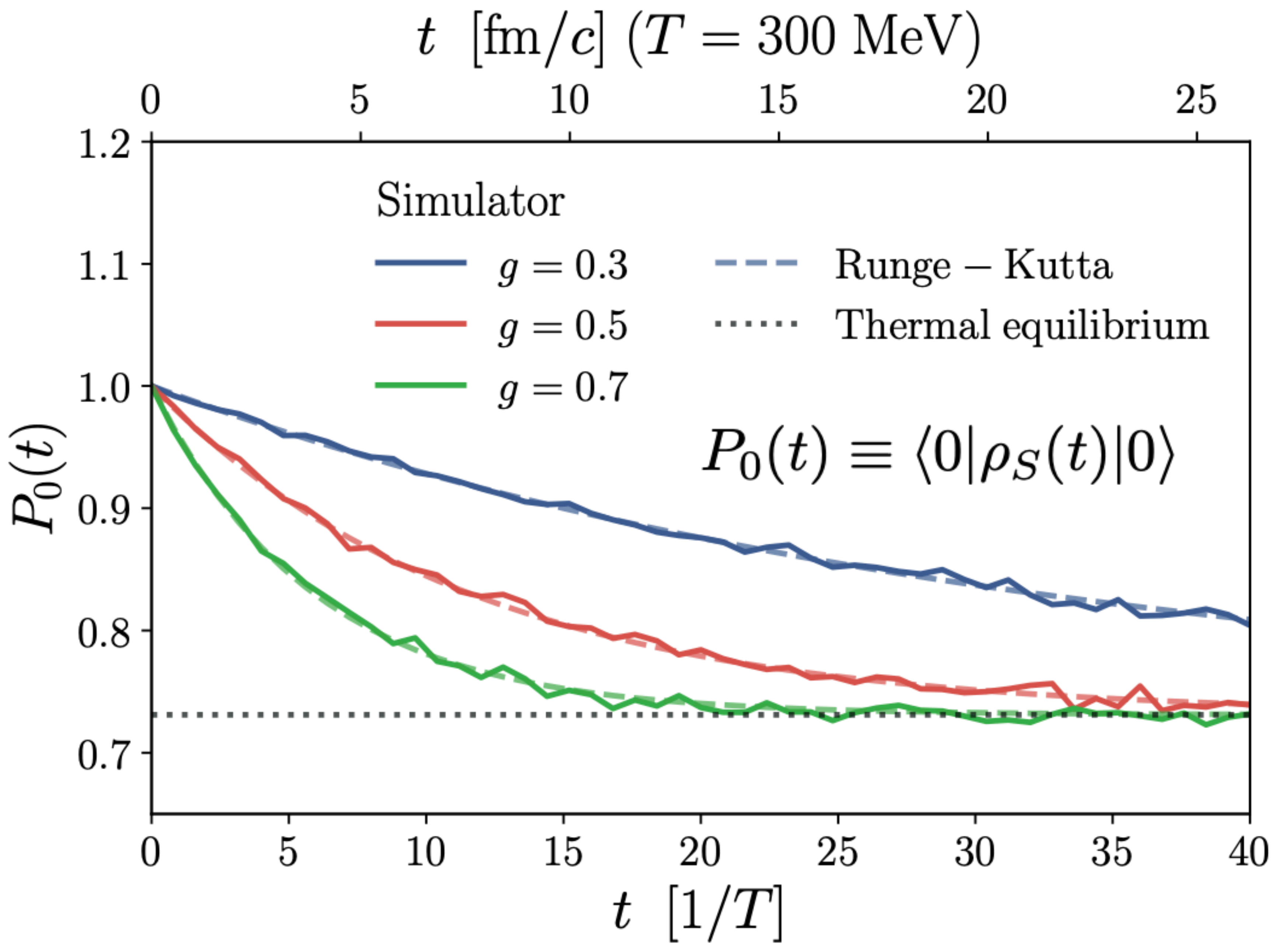
Quantum circuit for Lindbladian evolution







QIS for probes of nuclear matter

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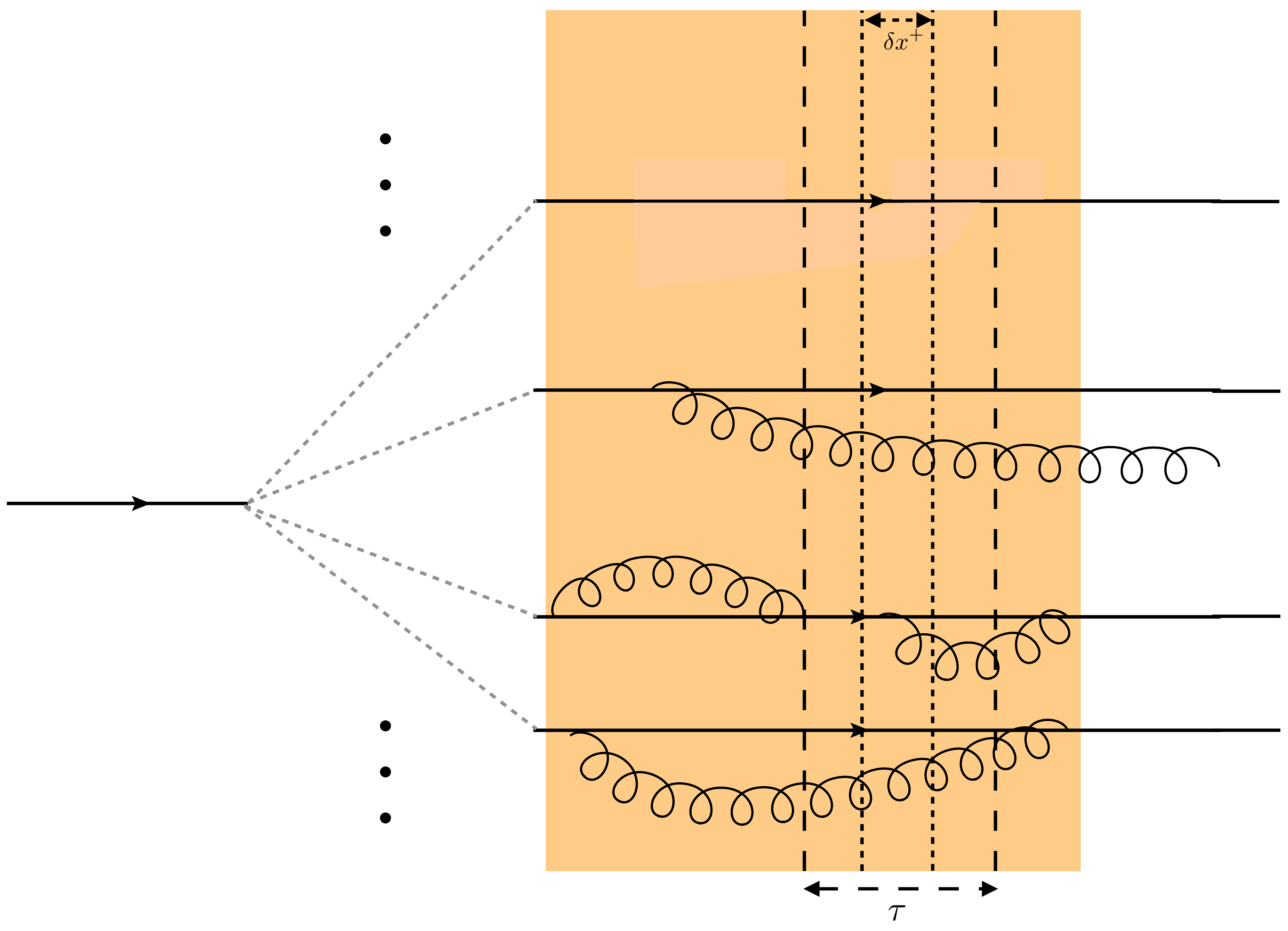
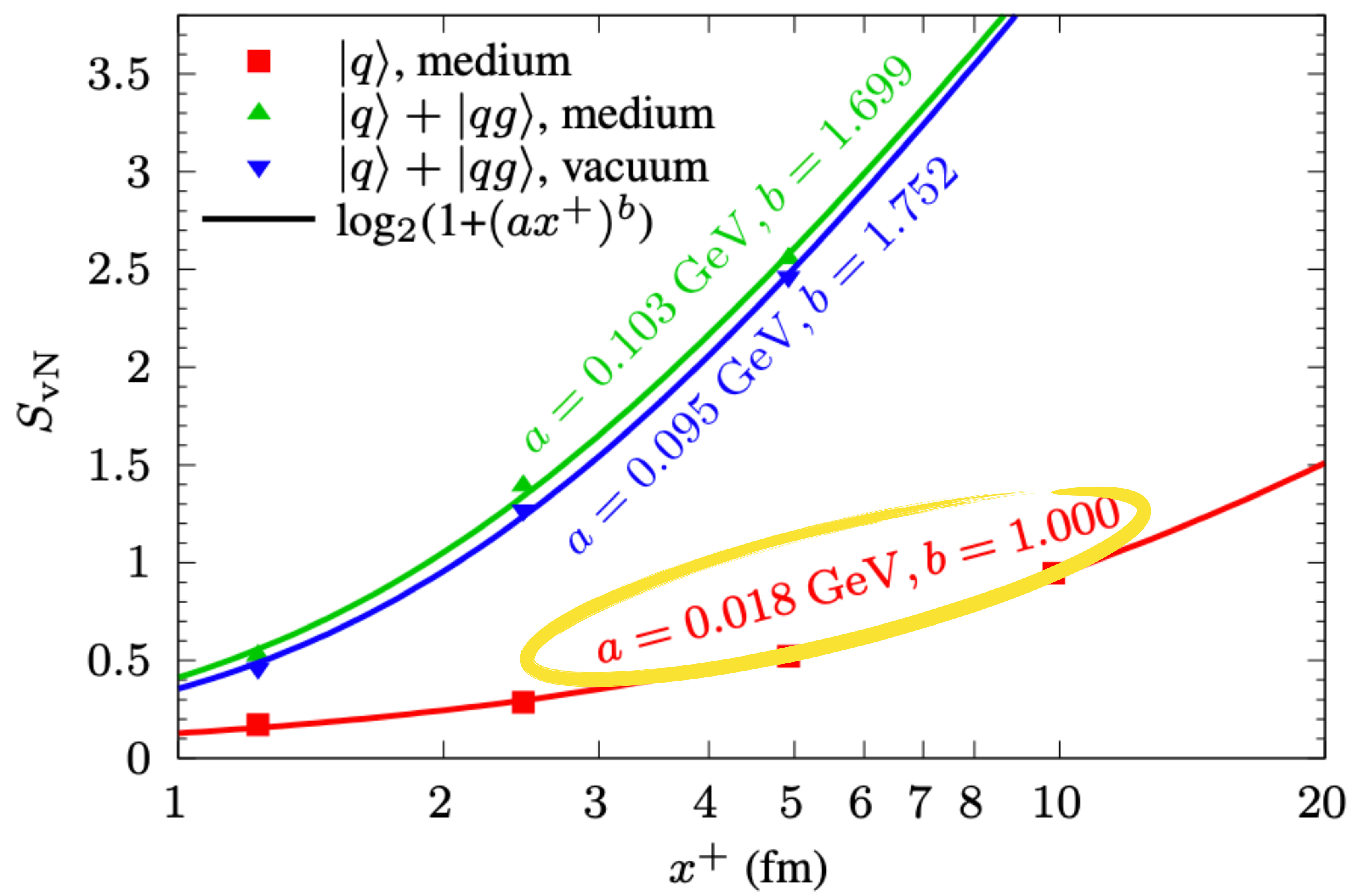
Light Front approach using CGC picture

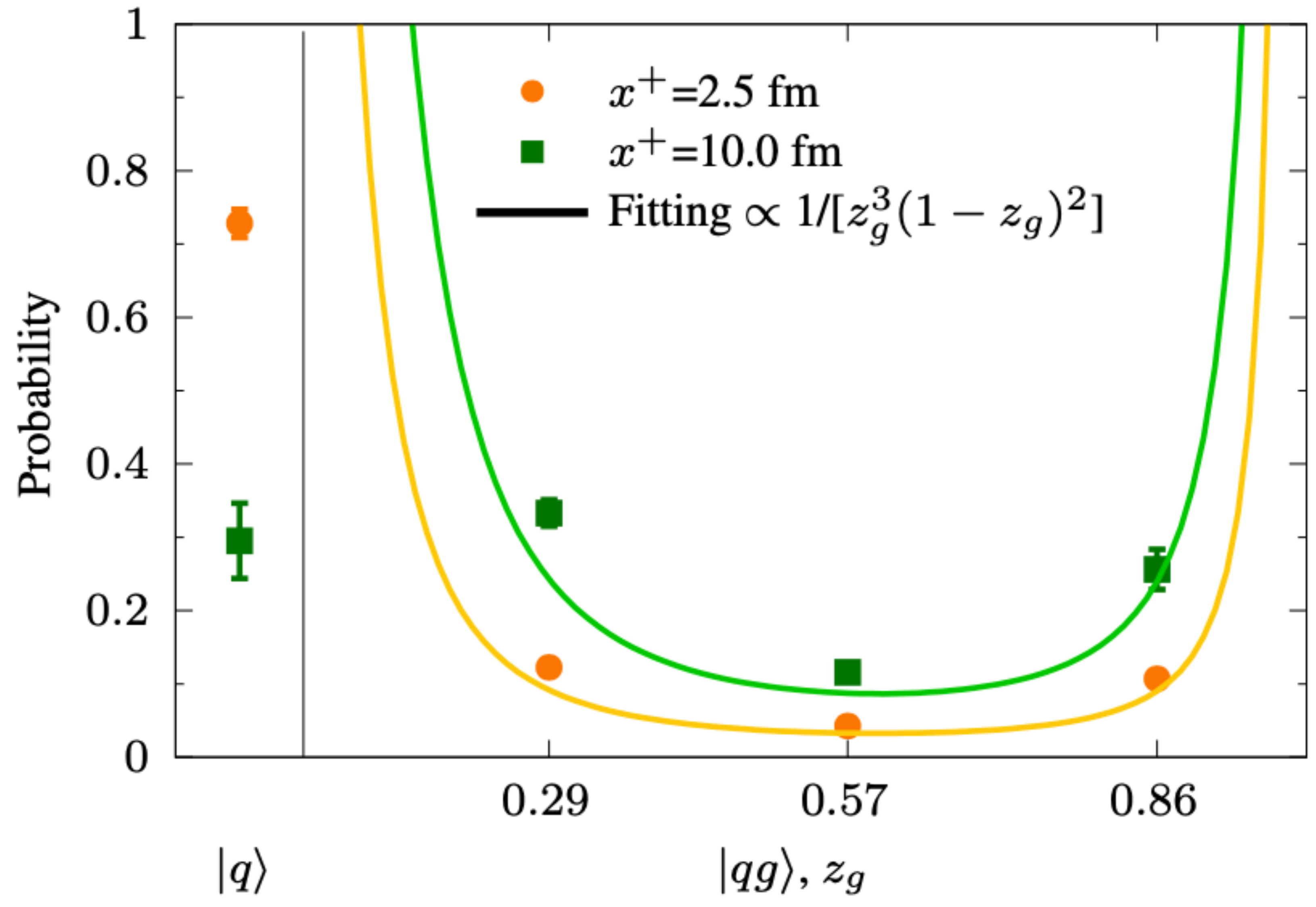
[JB et al, next week]



See also: [JB, Salgado, 2104.04661]
[Li, Lappi, Zhao, 2107.02225]
[JB et al, 2208.06750]
[Yao, 2205.07902]

[JB, Blaizot, Mehtar-Tani, 2305.10476]





Pair production

Schwinger effect: intense electric fields can lead to proliferation of particle pairs out of the vacuum

Pair-production rate computed in the semi-clasical limit (no back-reaction) [Schwinger, 1951]

Atomic Quantum Simulation of Dynamical Gauge Fields coupled to Fermionic Matter: From String Breaking to Evolution after a Quench

D. Banerjee[1], M. Dalmonte[2,3], M. Müller[4], E. Rico[2,3], P. Stebler[1], U.-J. Wiese[1], and P. Zoller[2,3,5]

Real-time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks

T. Pichler,[1] M. Dalmonte,[2,3] E. Rico,[4,5,6] P. Zoller,[2,3] and S. Montangero[1]

Schwinger pair production with ultracold atoms

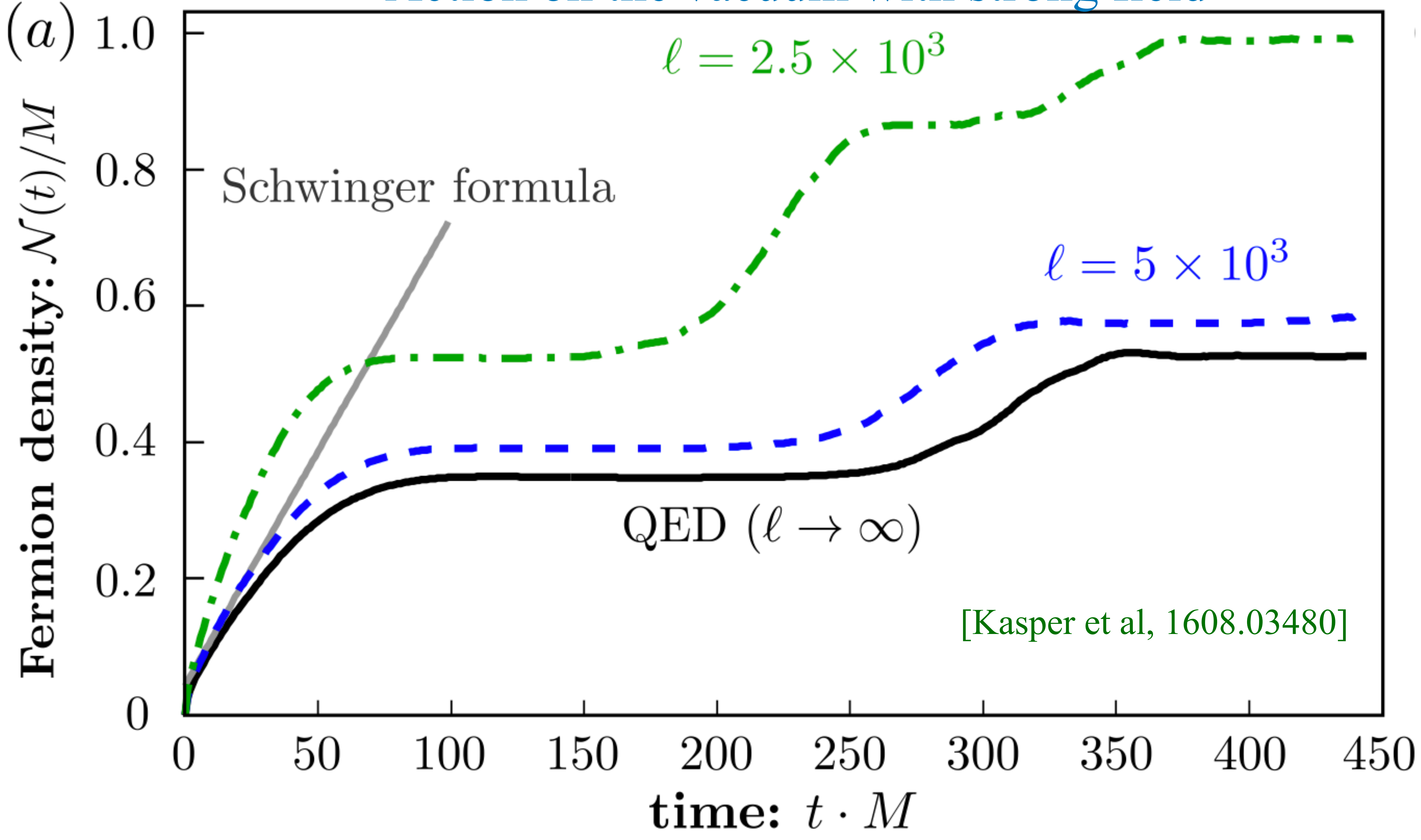
V. Kasper[a,*], F. Hebenstreit[b], M. K. Oberthaler[c], J. Berges[a]

Implementing quantum electrodynamics with ultracold atomic systems

V. Kasper,[1,2,*] F. Hebenstreit,[3] F. Jendrzejewski,[4] M. K. Oberthaler,[4] and J. Berges[1]

. . .

Action on the vacuum with strong field



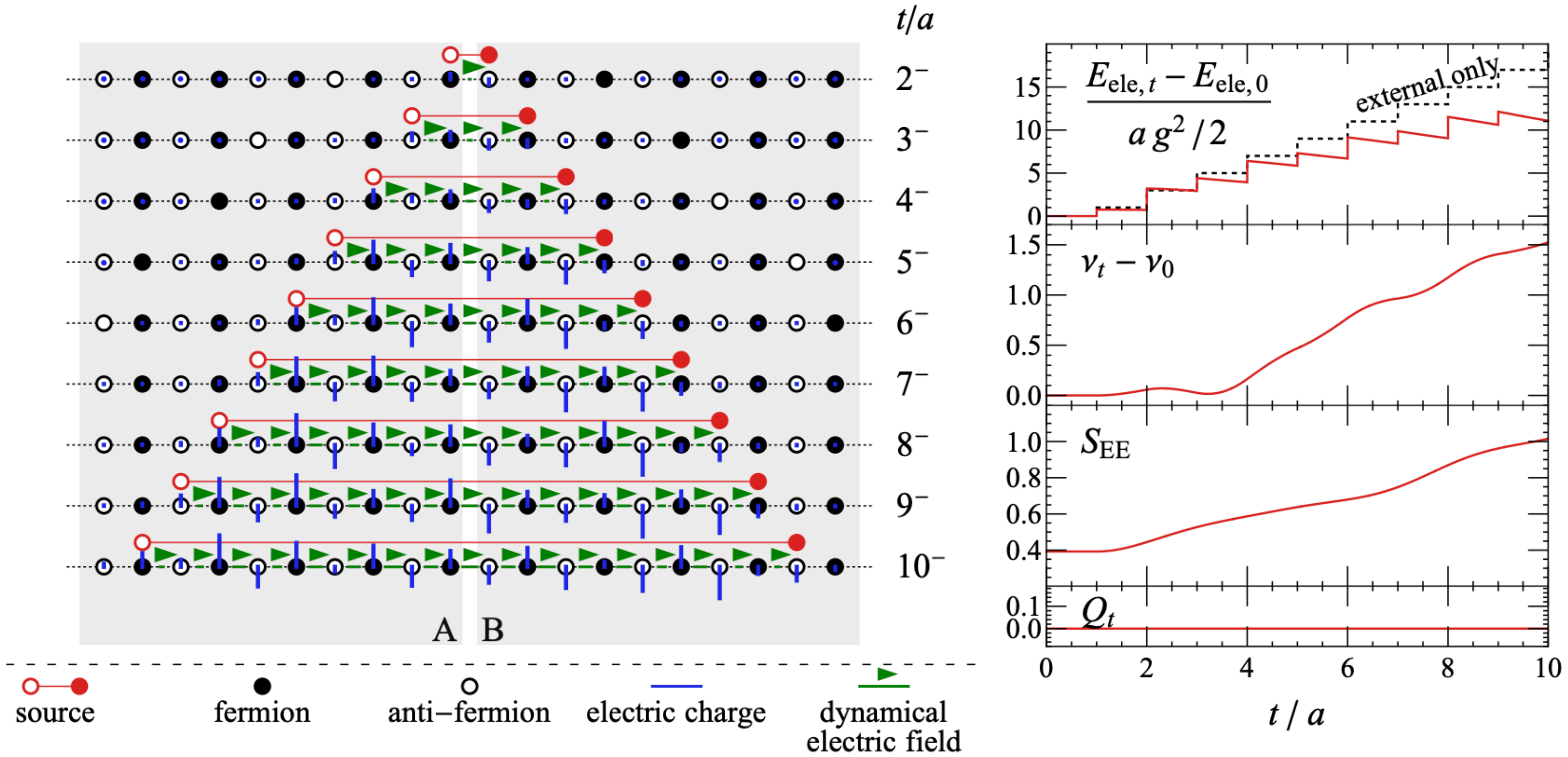
[Kasper et al, 1608.03480]

From pair production to QCD string breaking

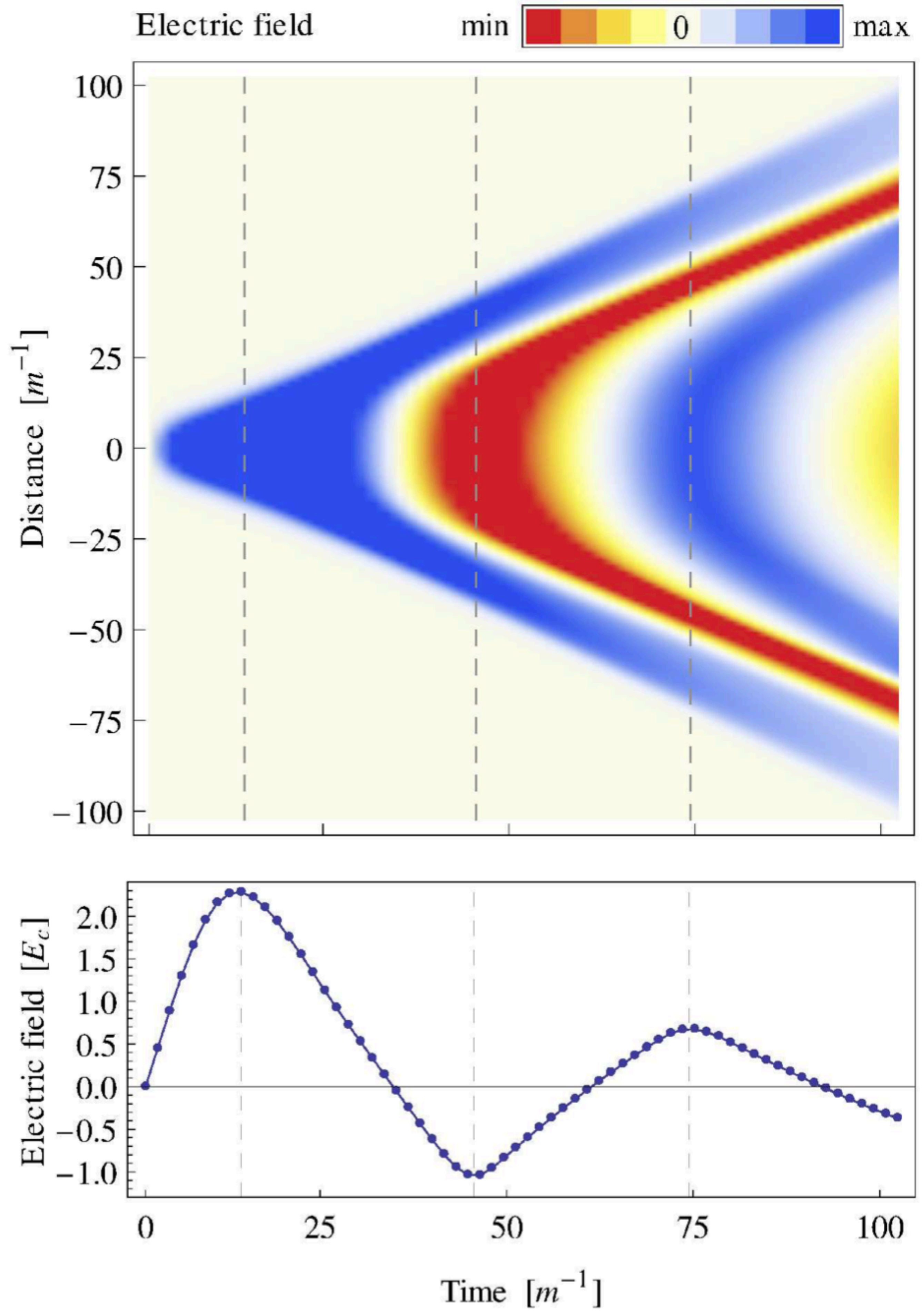
In QCD: Schwinger effect drives hadronization models, it is responsible for string breaking

Fully dynamical simulations exhibit multiple strings

Pair production modifies the vacuum in between fast moving charges



[Florio et al, 2301.11991]



[Hebenstreit, Berges, Gelfand, 1307.4619]

A simple model for jet induced modifications to the soft sector (?)

Spin correlations as probes of QCD strings

Brookhaven National Laboratory

Hyperon spin correlations might give access to QCD string evolution and entanglement spectrum

[Gong, Parida, Tu, Venugopalan, 2107.13007]

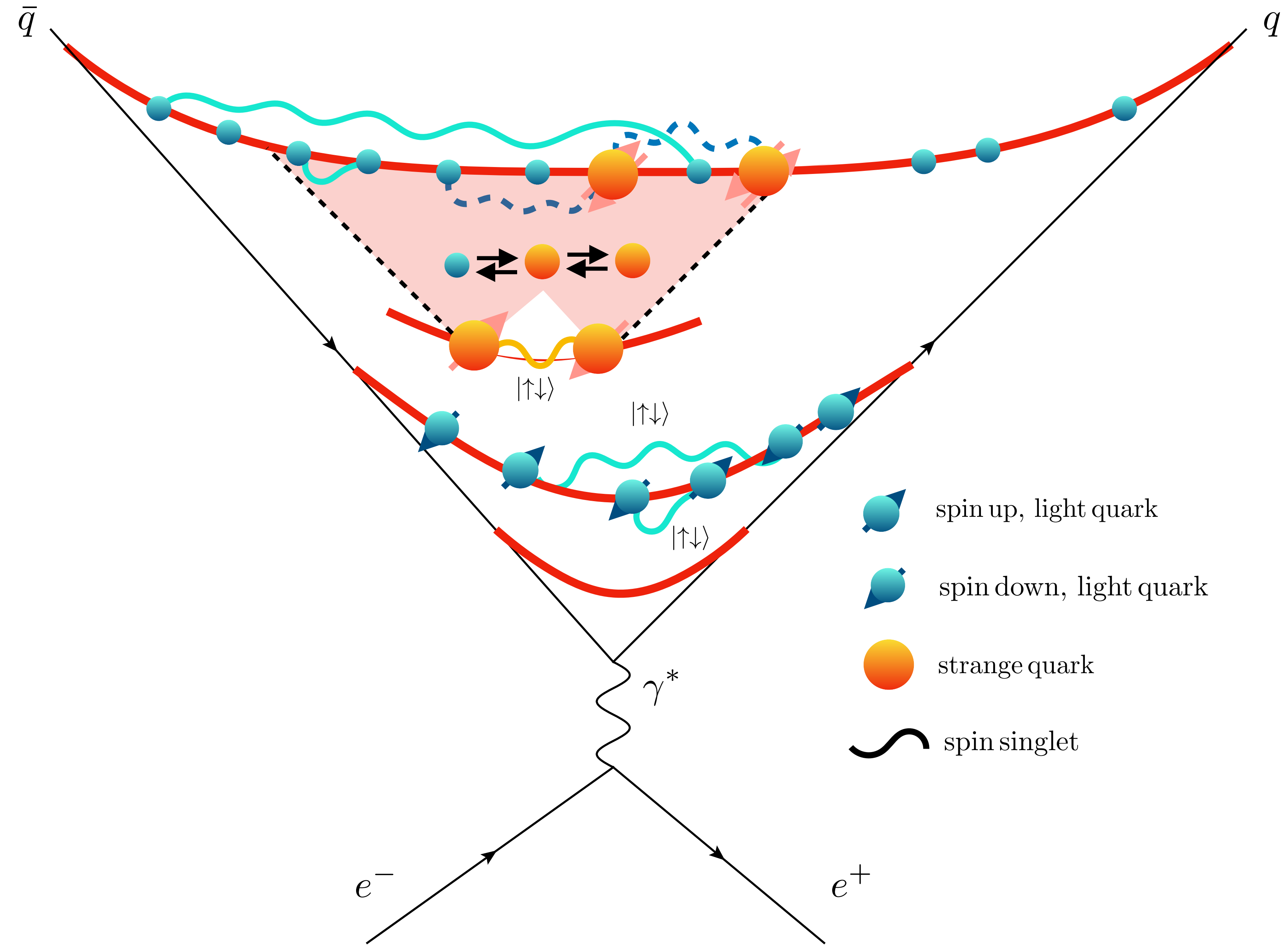
Entanglement in static string configurations

$$\frac{P(|\hat{n}_1\rangle, |\hat{n}_2\rangle)}{P(|\hat{n}_1\rangle)P(|\hat{n}_2\rangle)} = 1 - \frac{a}{(a+b/2)^2}\cos(\theta_2 - \theta_1)$$

a= # strange pairs b= # light quarks

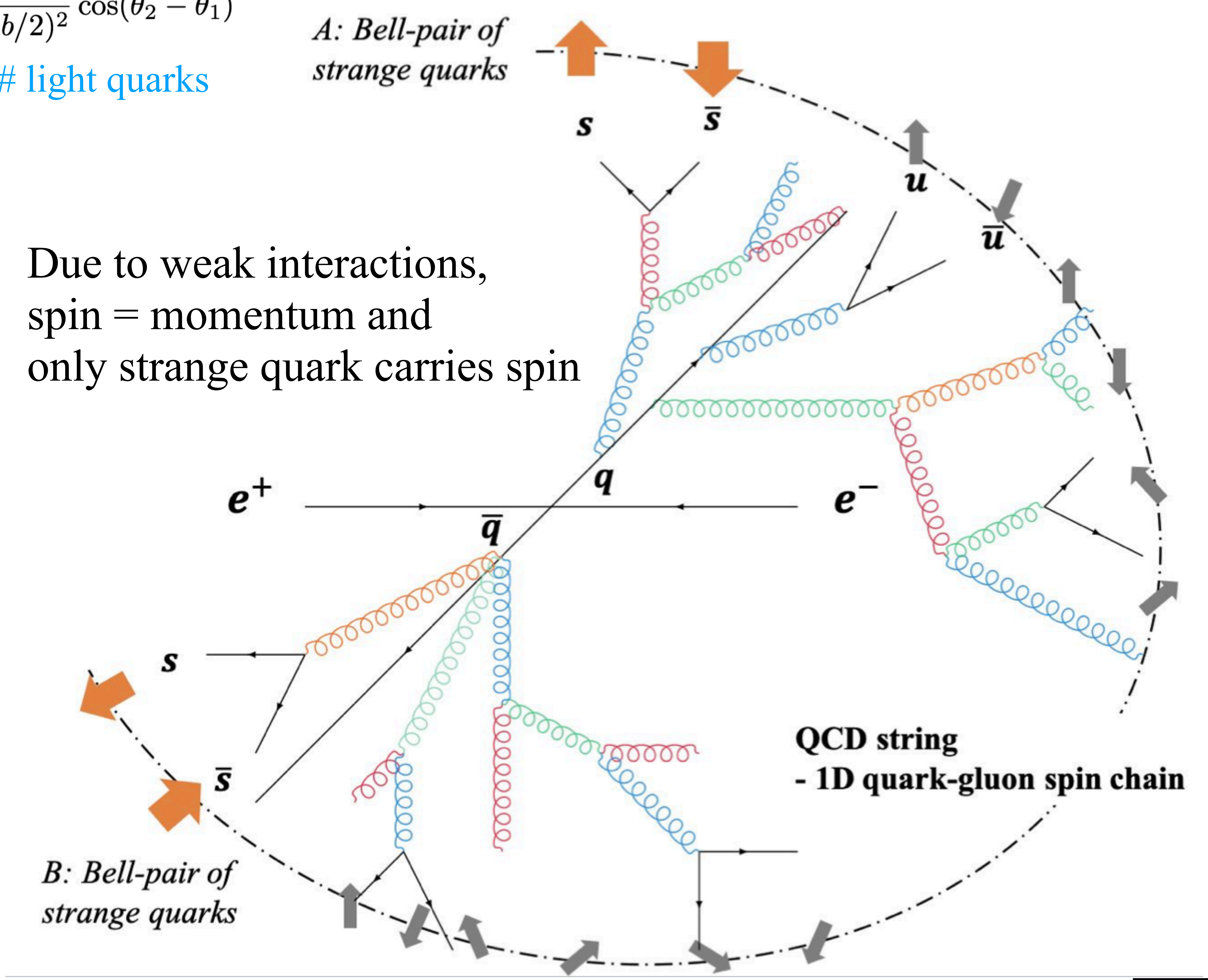
Corollary 2. *If the magnitude of the coefficient of* $\cos(\theta_{ab})$ *in a symmetric rotationally invariant correlation function is* $> \frac{1}{2}$*, then the measured state* ρ_{ab} *is entangled.*

Extended to 1+1d QFT with spin degrees of freedom



[JB, Gong, Venugopalan, 2306.xxxxx]

Due to weak interactions,
spin = momentum and
only strange quark carries spin



Thermalization in gauge theories

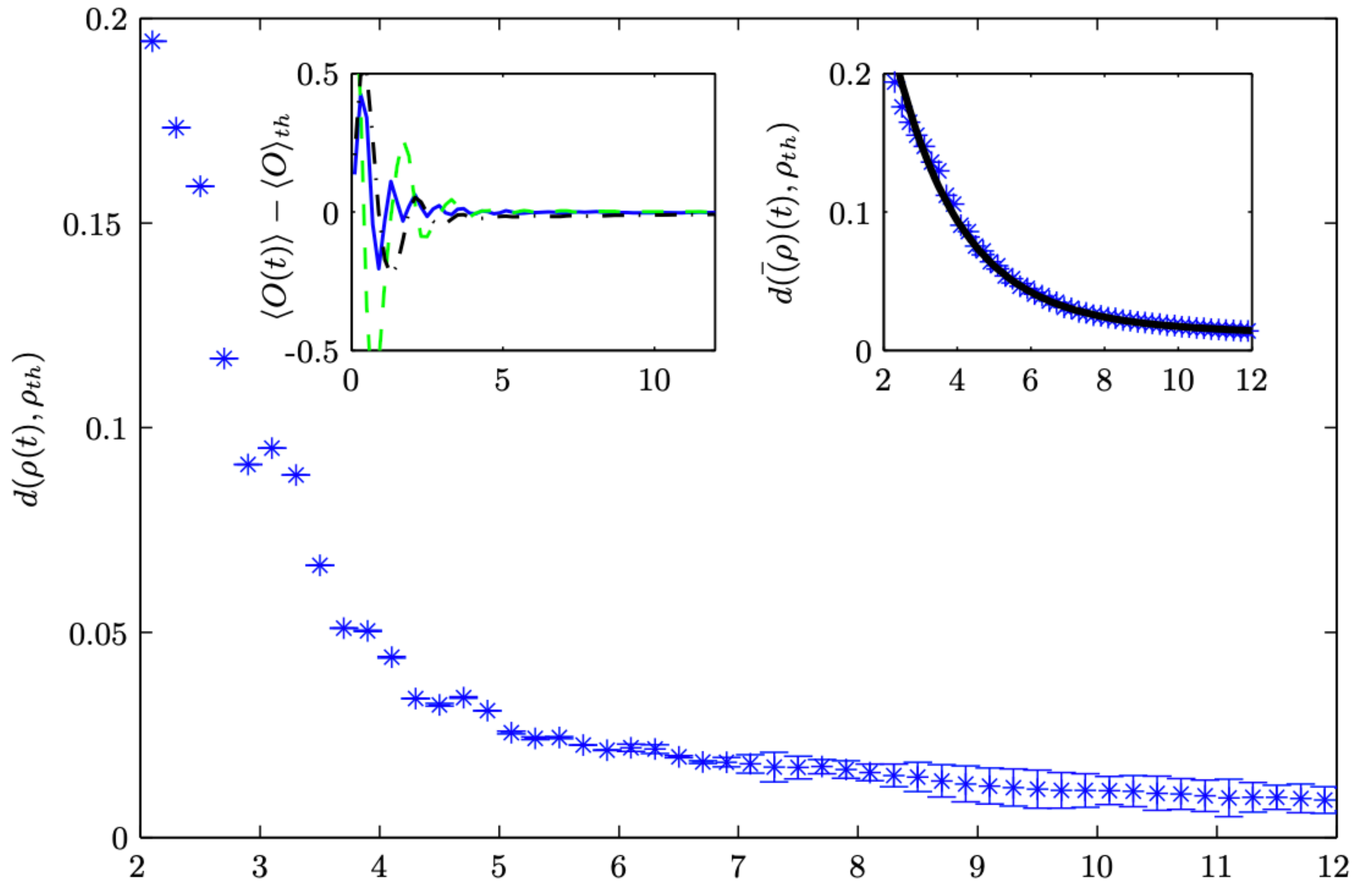
[Kinoshita, Wenger, Weiss, Nature 440, 2006]

Early studies driven by surprising experimental results for nearly integrable systems

Strong and weak thermalization of infinite non-integrable quantum systems

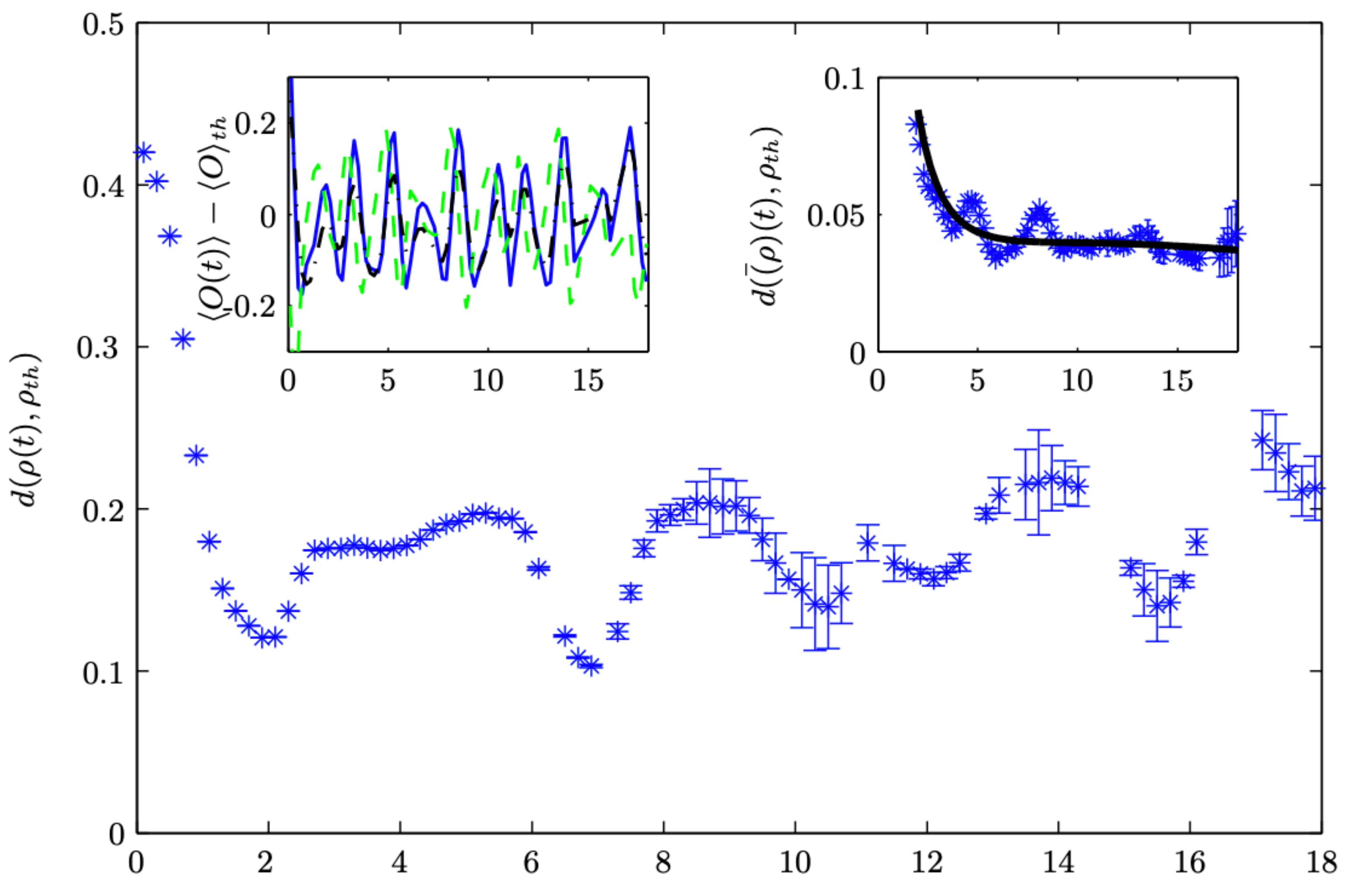
M. C. Bañuls,[1,*] J. I. Cirac,[1] and M. B. Hastings[2]

Initial state 1



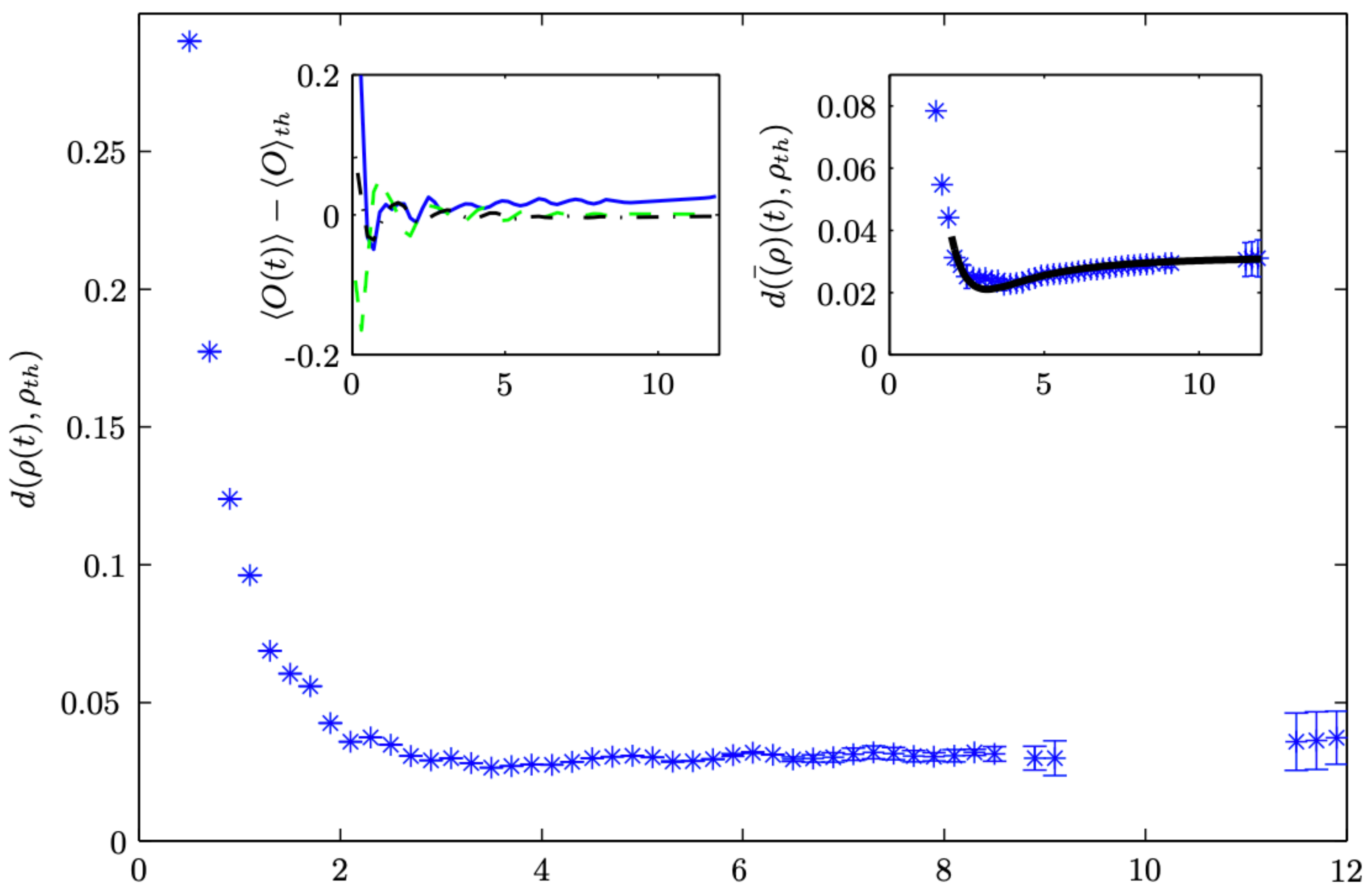
Strong thermalization

Initial state 2



Weak thermalization

Initial state 3



No thermalization

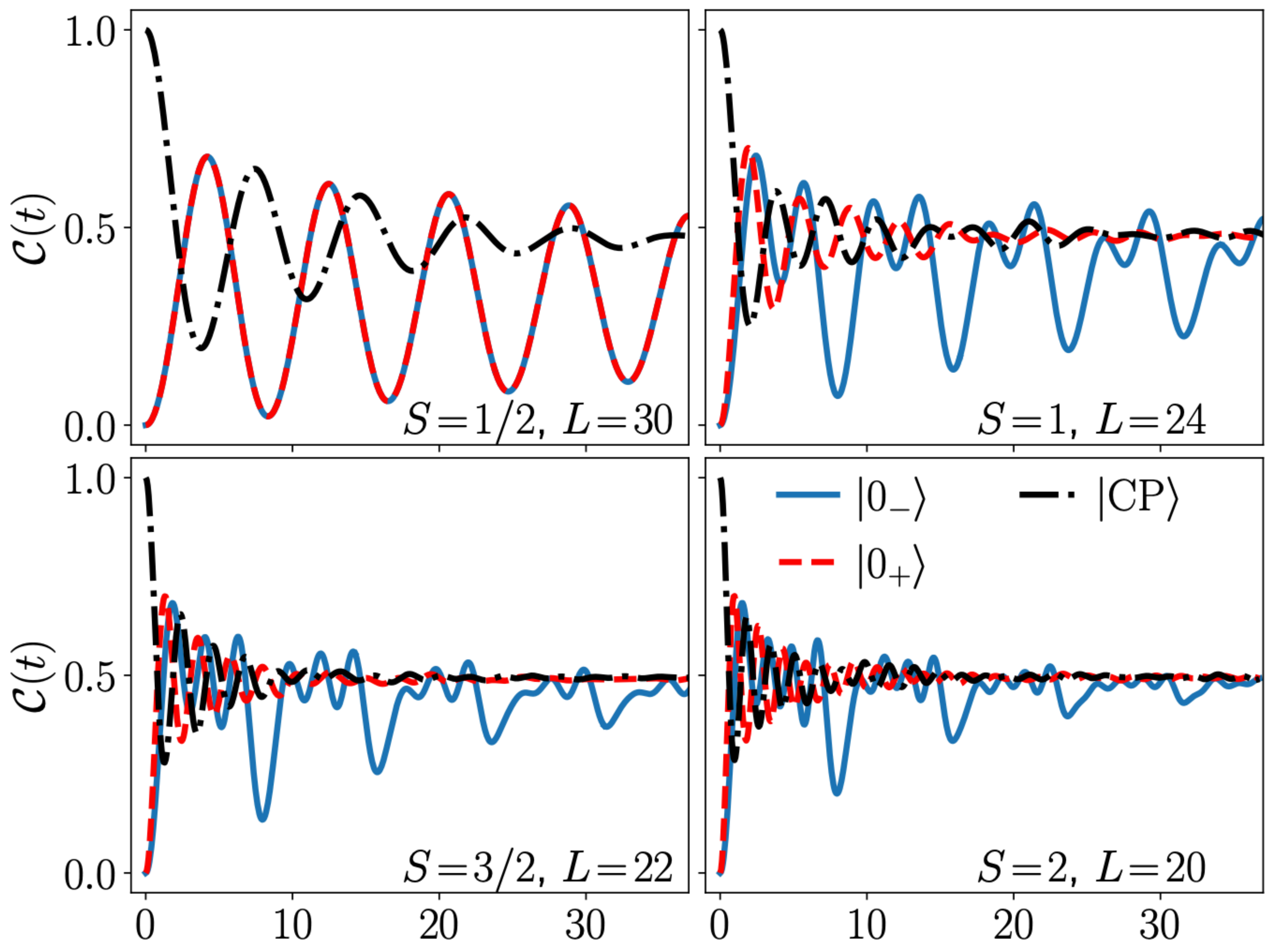
$$H = -\sum_i \sigma_z^{[i]} \otimes \sigma_z^{[i+1]} - g \sum_i \sigma_x^{[i]} - h \sum_i \sigma_z^{[i]}$$ (in general non-integrable)

Thermalization in gauge theories

Brookhaven National Laboratory

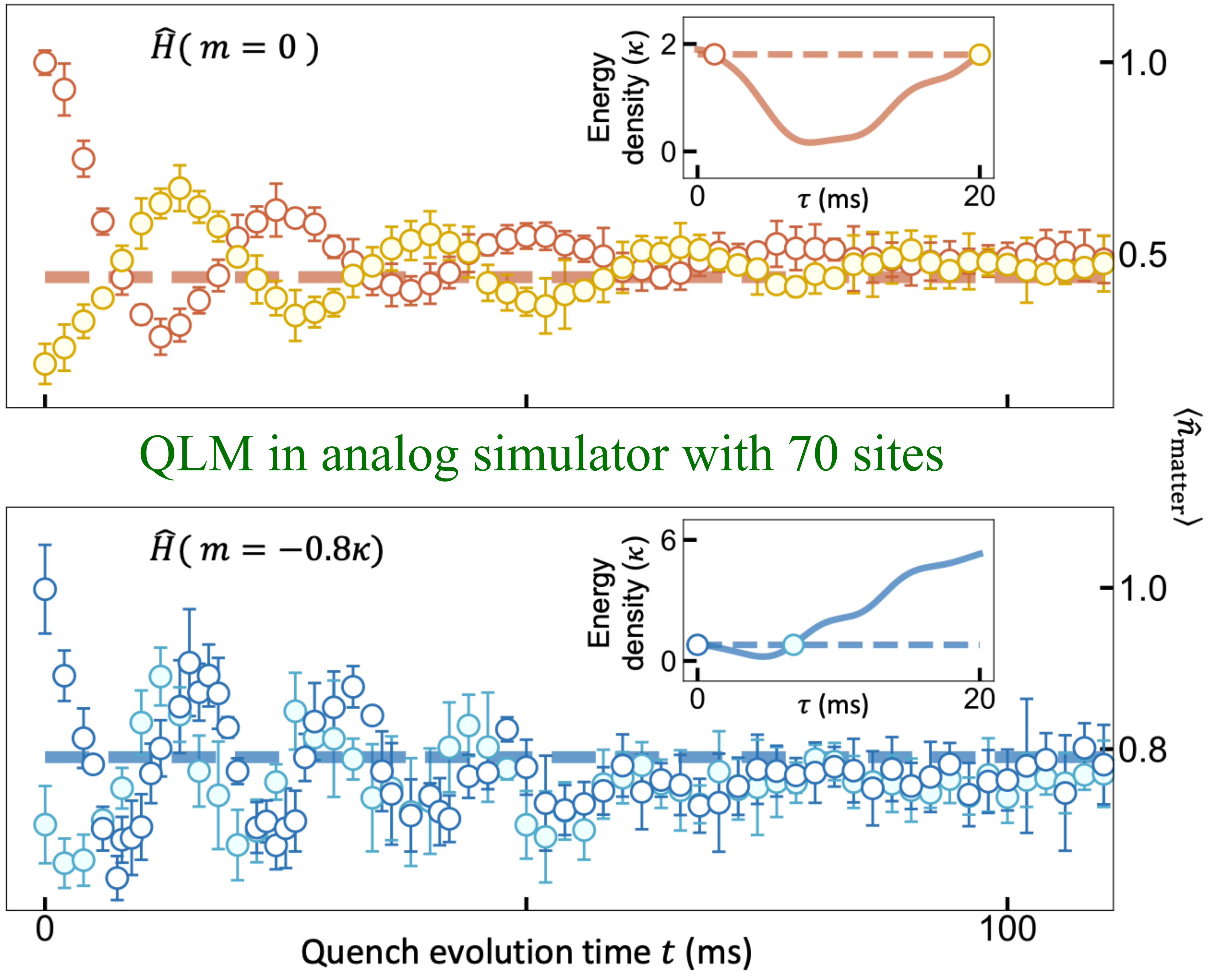
The same occurs in QLMs !

Chiral condensate for several initial conditions



[Desaules et al, 2203.08830]

For generic initial conditions = thermalization



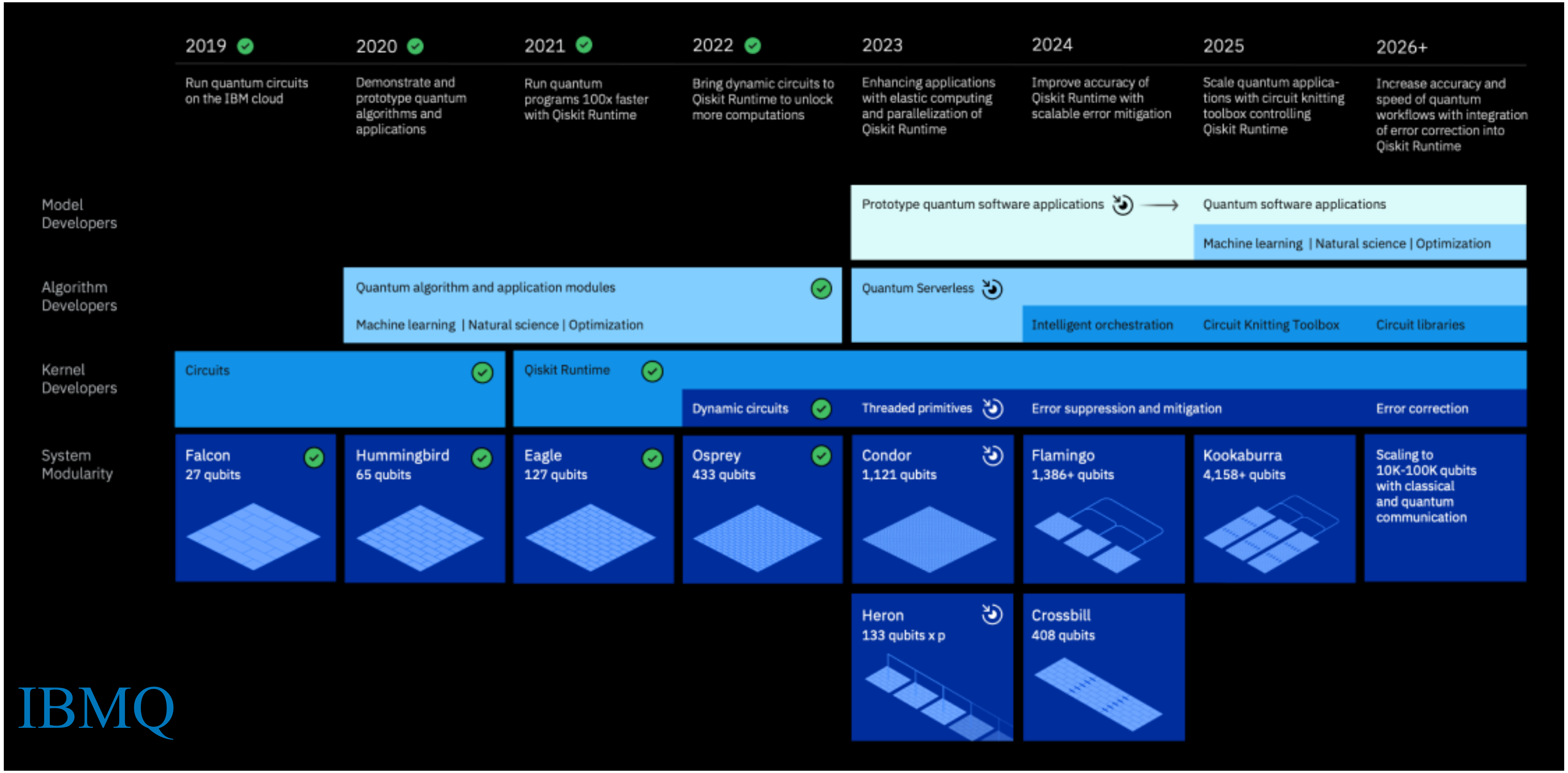
[Zhou et al, 2107.13563]

Connection to many interesting concepts in QFT: quantum scars, quantum chaos, out of time correlations, ETH, …

Some key ideas

1

QIS technologies are growing at a fast pace



Some key ideas

Brookhaven National Laboratory

2

Resurgence of old ideas under a new light

PHYSICAL REVIEW D VOLUME 13, NUMBER 4 15 FEBRUARY 1976

Strong-coupling calculations of lattice gauge theories: (1 + 1)-dimensional exercises

T. Banks and Leonard Susskind*
Tel Aviv University, Tel Aviv, Israel

John Kogut†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 25 August 1975)

1975

Atomic Quantum Simulation of Dynamical Gauge Fields coupled to Fermionic Matter: From String Breaking to Evolution after a Quench

D. Banerjee[1], M. Dalmonte[2,3], M. Müller[4], E. Rico[2,3], P. Stebler[1], U.-J. Wiese[1], and P. Zoller[2,3,5]

2012

MORE ABOUT THE MASSIVE SCHWINGER MODEL*

Sidney Coleman

Lyman Laboratory of Physics
Harvard University
Cambridge, Mass. 02138

1976

Implementing quantum electrodynamics with ultracold atomic systems

V. Kasper,[1,2,*] F. Hebenstreit,[3] F. Jendrzejewski,[4] M. K. Oberthaler,[4] and J. Berges[1]

2016

Some key ideas

3

There is a wealth of other works I did not cover

Lattice Gauge Theory applications

Entanglement measures and non-pert. QCD

Foundations of QM in the LHC era

Phase structure of Gauge Theories

Chiral dynamics

Back ups

Review papers

Brookhaven National Laboratory

Quantum Simulation for HEP

2204.03381

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Quantum Simulation for High Energy Physics

Quantum Computers and Simulators for Lattice

1911.00003

Simulating Lattice Gauge Theories within Quantum Technologies

M.C. Bañuls[1,2], R. Blatt[3,4], J. Catani[5,6,7], A. Celi[3,8], J.I. Cirac[1,2], M. Dalmonte[9,10], L. Fallani[5,6,7], K. Jansen[11], M. Lewenstein[8,12,13], S. Montangero[7,14 a], C.A. Muschik[3], B. Reznik[15], E. Rico[16,17 b], L. Tagliacozzo[18], K. Van Acoleyen[19], F. Verstraete[19,20], U.-J. Wiese[21], M. Wingate[22], J. Zakrzewski[23,24], and P. Zoller[3]

Review papers

Introduction to Tensor Networks 1306.2164

A Practical Introduction to Tensor Networks:
Matrix Product States and Projected Entangled Pair States

Román Orús *

Thermalization in QCD and applications of quantum technologies 2005.12299

QCD thermalization: *Ab initio* approaches and interdisciplinary connections

Jürgen Berges*
Institute for Theoretical Physics, Heidelberg University,
Philosophenweg 16, D-69120 Heidelberg, Germany

Michal P. Heller†
Max Planck Institute for Gravitational Physics
(Albert Einstein Institute),
Am Mühlenberg 1, D-14476 Potsdam, Germany

Aleksas Mazeliauskas‡
Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland

Raju Venugopalan§
Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

Review papers

Brookhaven National Laboratory

Quantum computing resources and references

https://qiskit.org