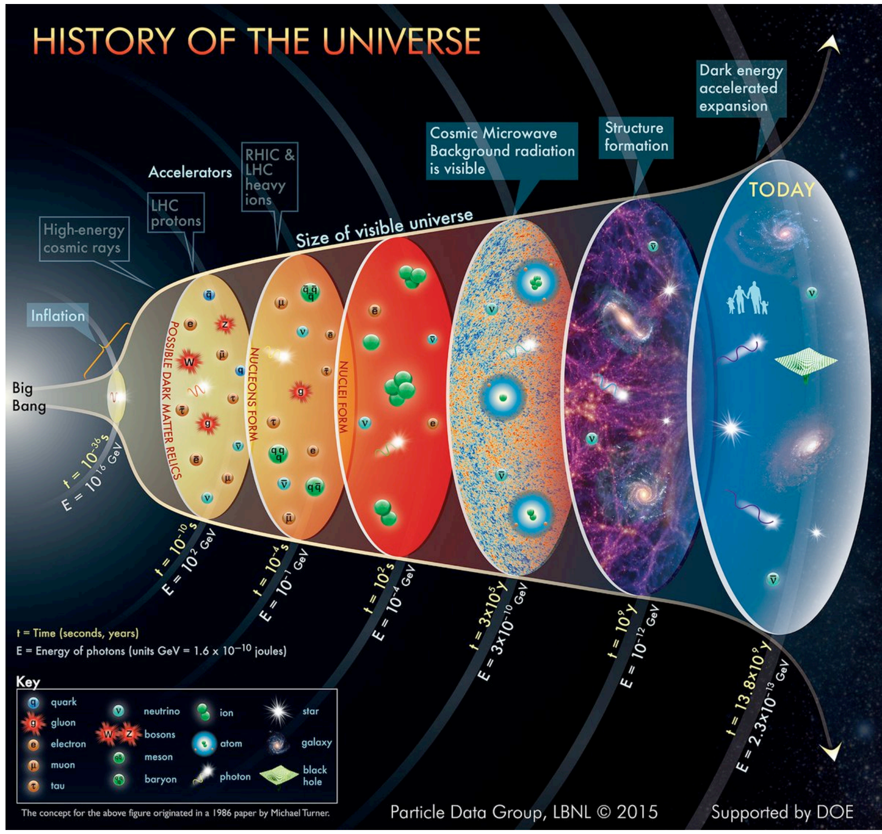
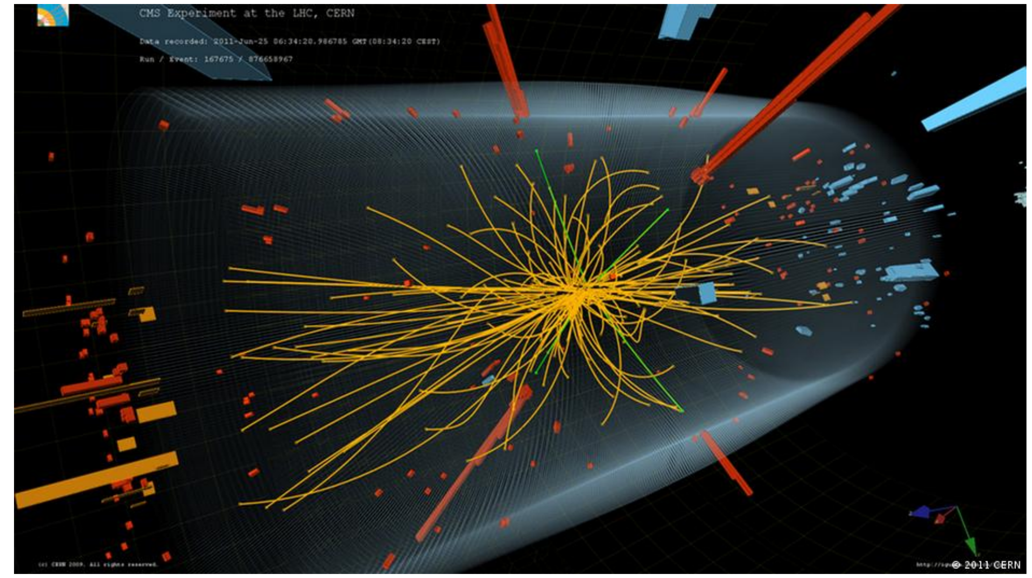
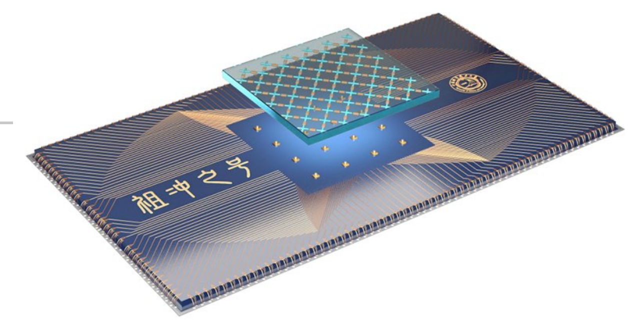






中国科学技术大学
University of Science and Technology of China

Ying-Ying Li (李英英)

yingyingli@ustc.edu.cn

Quantum Computing for High Energy Physics

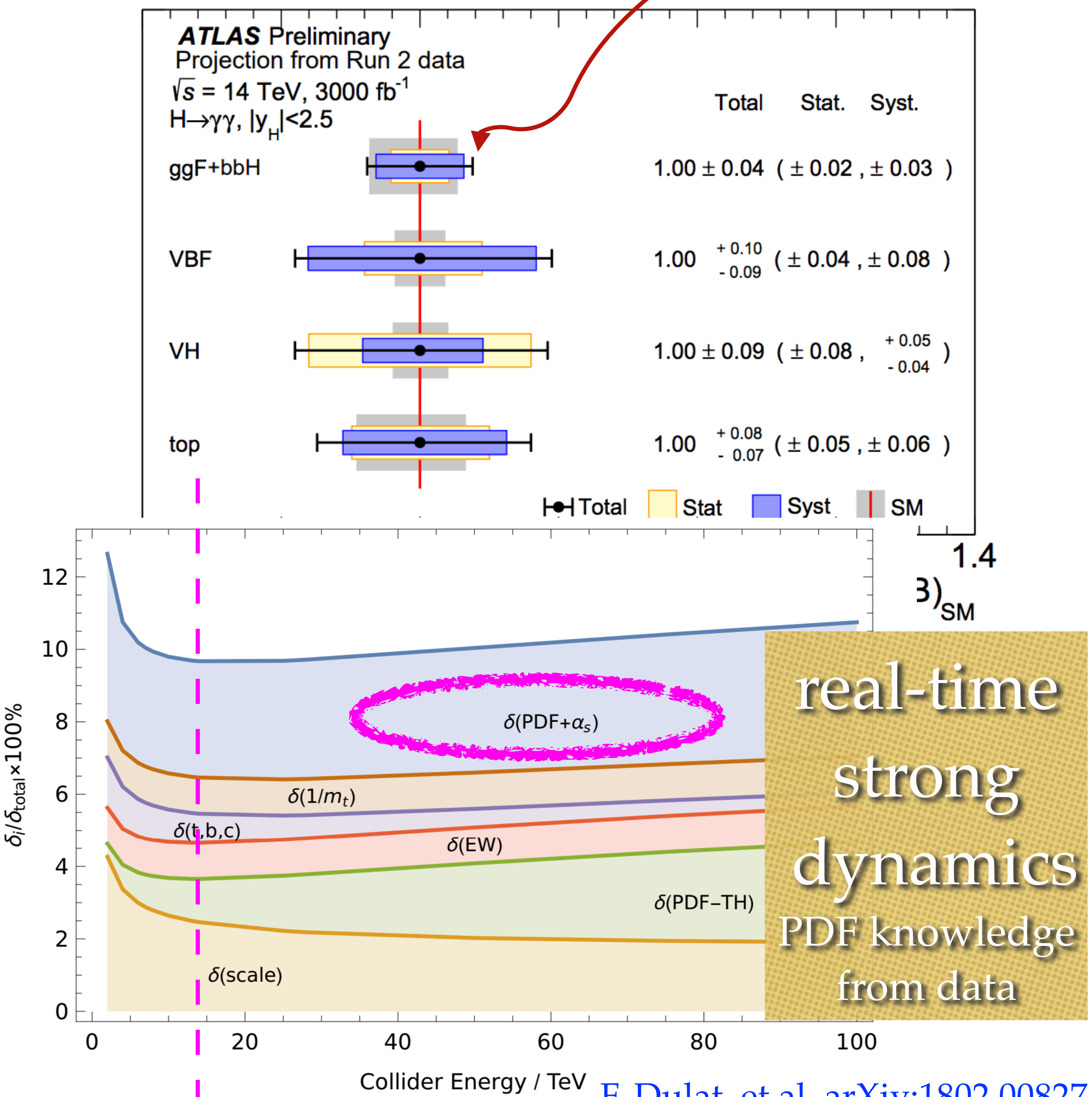
Dec. 17, 2023@第十七届TeV工作组学术研讨会

Theoretical inputs to colliders

theoretical uncertainties

real-time dynamics $\langle \text{out} | e^{-iH[\psi]t} | \text{in} \rangle$

PDF



F. Dulat, et al, arXiv:1802.00827
M. Cepeda, et al, arXiv:1902.00134

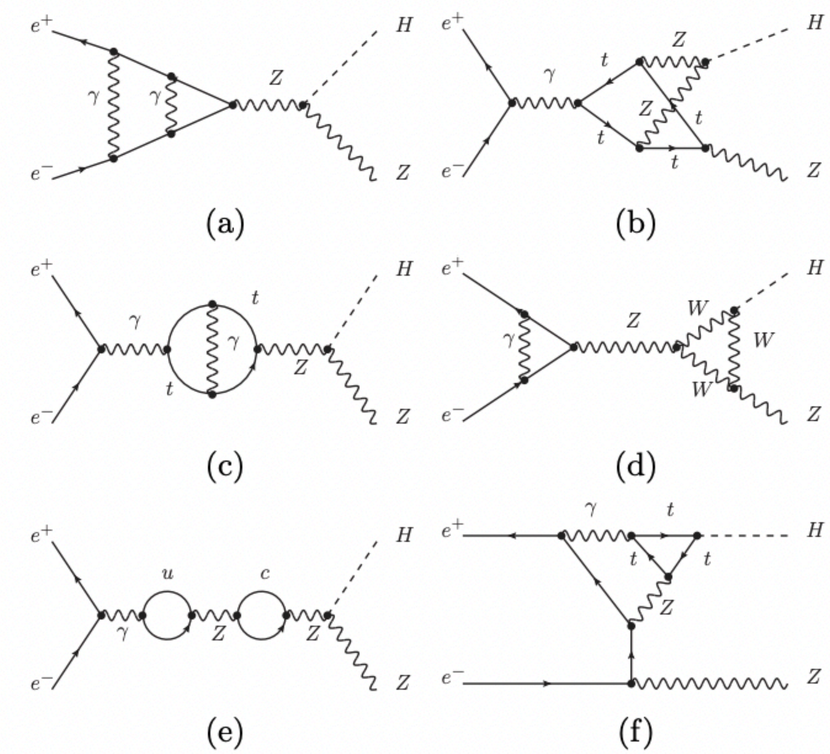
higher order corrections

CEPC : $\sigma(e^+e^- \to ZH), 0.51\%$

NLO EW
NNLO EW-QCD

1%

complete two loop



F. An, et al, arXiv:1810.09037
Y. Gong et al., Q. -F. Sun et al.,
X. Chen et al., arXiv: 2209.14953

Why Quantum Computing

lattice non-perturbative calculations

$$\langle O \rangle = \frac{\sum_{\mathcal{C}} O(\mathcal{C}) W(\mathcal{C})}{\sum_{\mathcal{C}} W(\mathcal{C})}$$

Imaginary time problem : $W(\mathcal{C}) \sim \exp(-S(\mathcal{C}))$

complex $S(\mathcal{C})$ for non vanishing θ

real-time dynamics, finite density…

Sign Problem!!!

configuration space $\mathcal{C}$ is exponentially large in system size

out-of-equilibrium,
non-perturbative
higher order processes,
quantum interference
cannot be solved classically
due to theoretical or
computational limitations:

sign problem or rare events that has exponential-scaling of the complexity

Why Quantum Computing

lattice non-perturbative calculations

$$\langle O \rangle = \frac{\sum_{\mathcal{C}} O(\mathcal{C}) W(\mathcal{C})}{\sum_{\mathcal{C}} W(\mathcal{C})}$$

Imaginary time problem : $W(\mathcal{C}) \sim \exp(-S(\mathcal{C}))$

complex $S(\mathcal{C})$ for non vanishing θ

real-time dynamics, finite density…

Sign Problem!!!

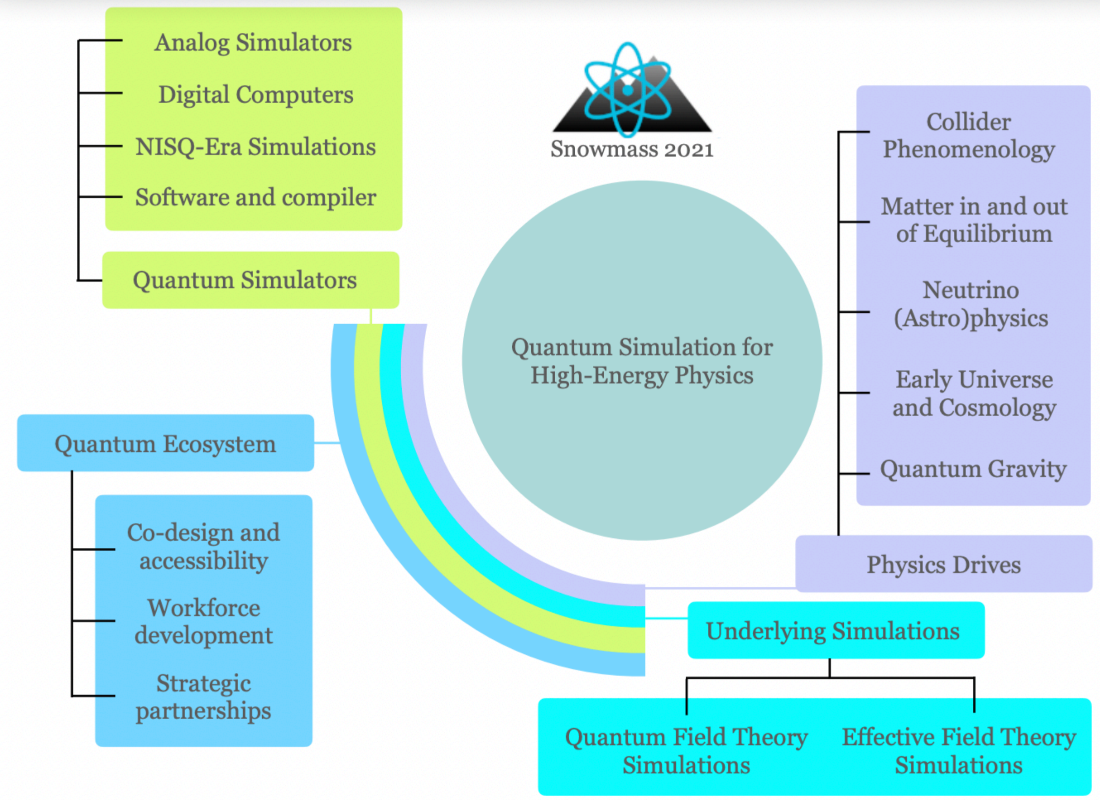
configuration space $\mathcal{C}$ is exponentially large in system size

$$\langle x | e^{-iHt} | y \rangle = \int \mathcal{D}\phi e^{iS}$$

[*PRX Quantum* 4 (2023) 2, 027001]

Quantum Simulation for High Energy Physics

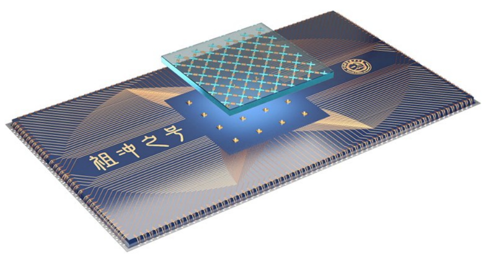
Christian W. Bauer,[1,a] Zohreh Davoudi,[2,b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[5] Junyu Liu,[14,15] Mikhail Lukin,[16] Yannick Meurice,[17] Christopher Monroe,[18,19,20,21] Benjamin Nachman,[1] Guido Pagano,[22] John Preskill,[23] Enrico Rinaldi,[24,25,26] Alessandro Roggero,[27,28] David I. Santiago,[29,30] Martin J. Savage,[31] Irfan Siddiqi,[29,30,32] George Siopsis,[33] David Van Zanten,[5] Nathan Wiebe,[34,35] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[36] and Silvia Zorzetti[5]

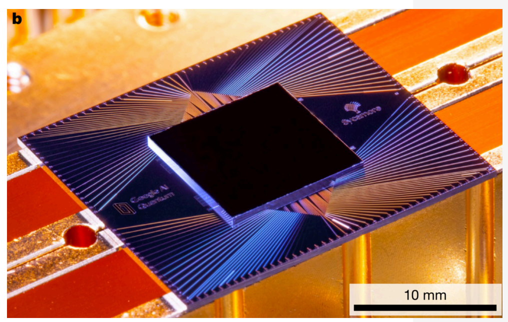


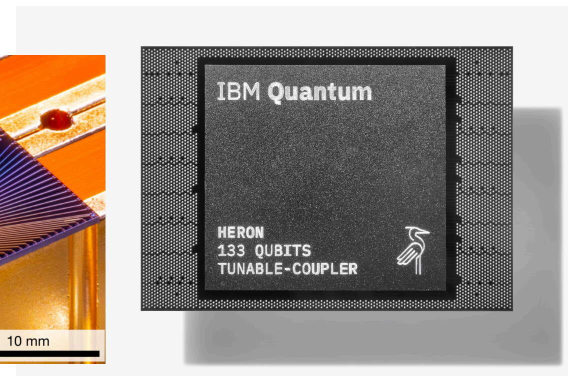
Rapidly improving universal quantum computing hardware

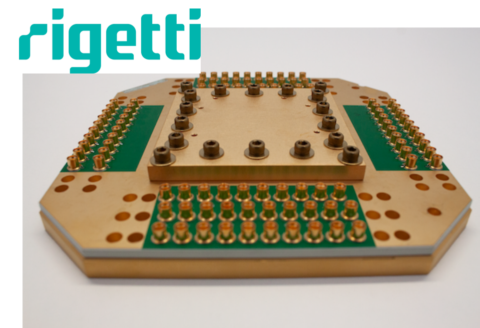
Superconducting Processor

multi-chip quantum processor









176 qubits

54 qubits

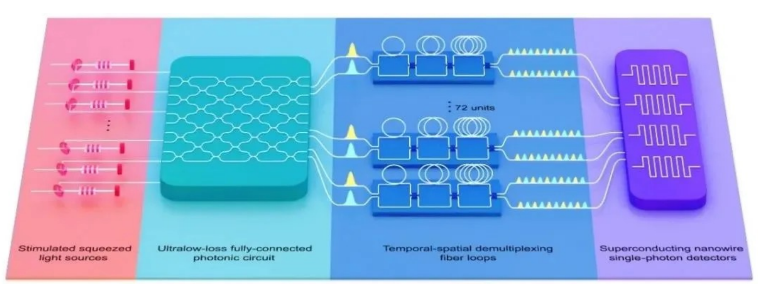
1121 qubits
access to 133 qubits

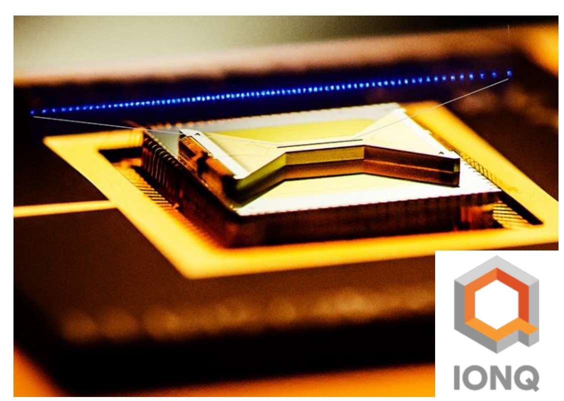
80 qubits

Photon qubits

trapped ion qubits

neutral atoms
48 logical Qubits, hundreds of entangling logical operations

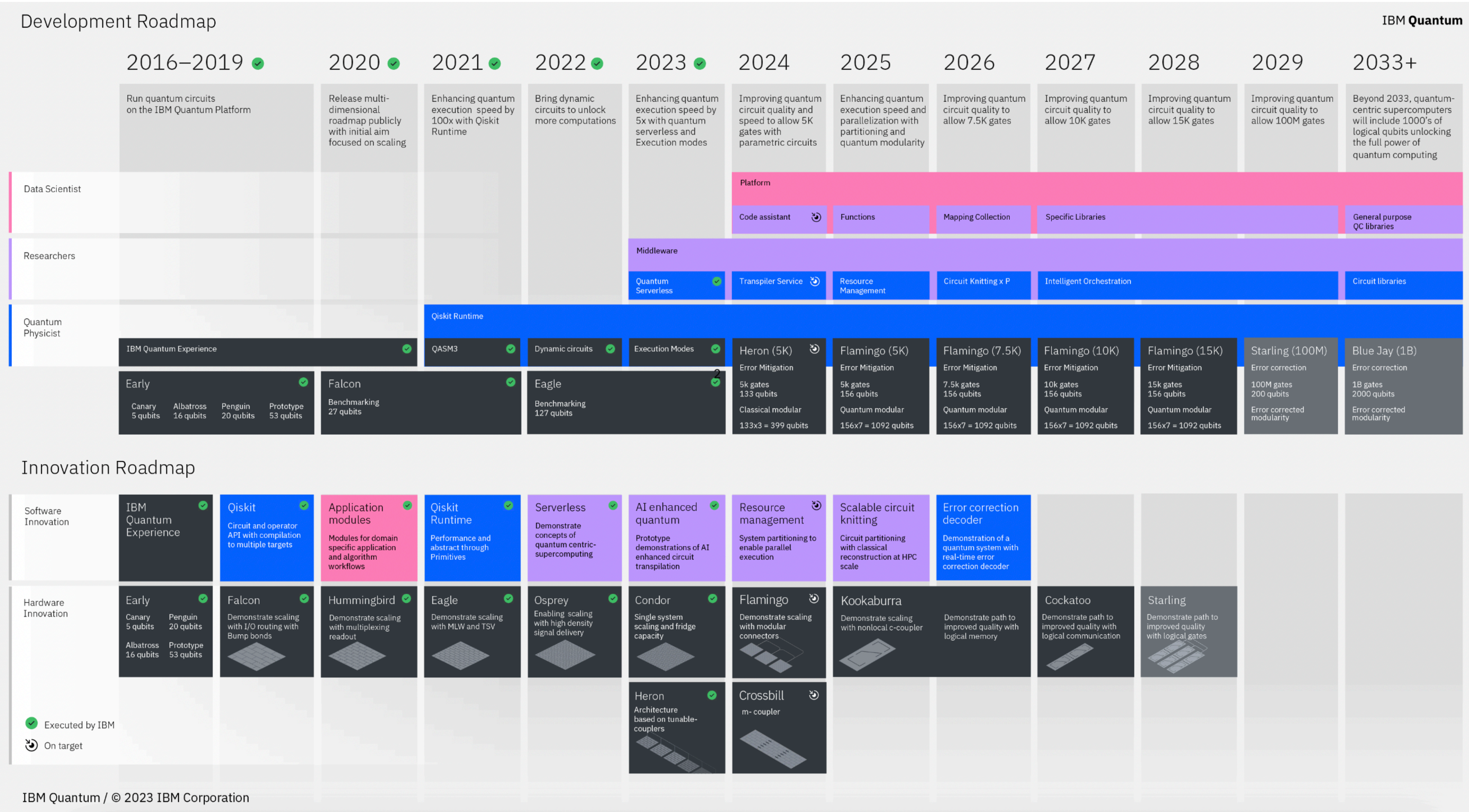




九章三号 - 255 qubits

22 qubits

Rapidly improving universal quantum computing hardware

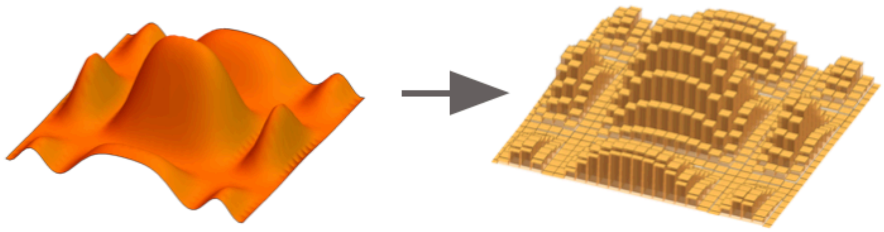


Quantum Simulation for Quantum Field Theory

Bosonic and fermionic DOF,
Dynamical and coupled global and local (gauge) symmetries,
Relativistic - particle number non-conservation,
Nontrivial vacuum state in strongly interacting theories

"Galactic Algorithms"

Discretization



KS Hamiltonian

Digitization

$$|q\rangle^N \to |G\rangle$$

truncation, discrete subgroup, …

Initialization

$$\mathcal{U}\,|G\rangle^L \to |\psi_0\rangle$$

ground/thermal/particle state prep

Propagation

$$\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$$

Trotterization, variational approach, Taylor series, …

Evaluation

$$\langle \mathcal{O} \rangle$$

Parton distribution function, particle decay, …

Error mitigation

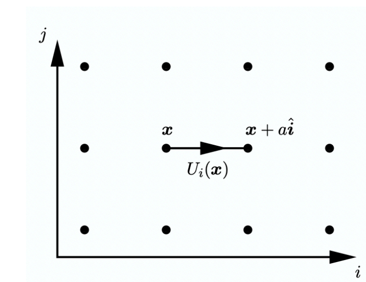
See references in [M. Carena, H. Lamm, **YYL**, W. Liu, PRD. **104**, 094519]

Discretization 

infinities in QFT

$$H = \int d^d x \mathrm{Tr}\left(\boldsymbol{E}^2 + \boldsymbol{B}^2\right) \qquad U_\square = \exp\left\{ig \oint_\square A \cdot dx\right\}$$

gauge invariance



$$U_i(x) = e^{ig \int_a^0 dt A_i(x + t\hat{i})}$$

Kogut and Susskind formulation: [Phys. Rev. D **11**, 395 (1975)]

$$H = -t \sum_{\langle xy \rangle} s_{xy} \left(\psi_x^\dagger U_{xy} \psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m \sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2} \sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2} \sum_\square \mathrm{Tr}\left(U_\square + U_\square^\dagger\right)$$

fermion kinetic — fermion mass — energy of electric field — energy of magnetic field

Discretization 

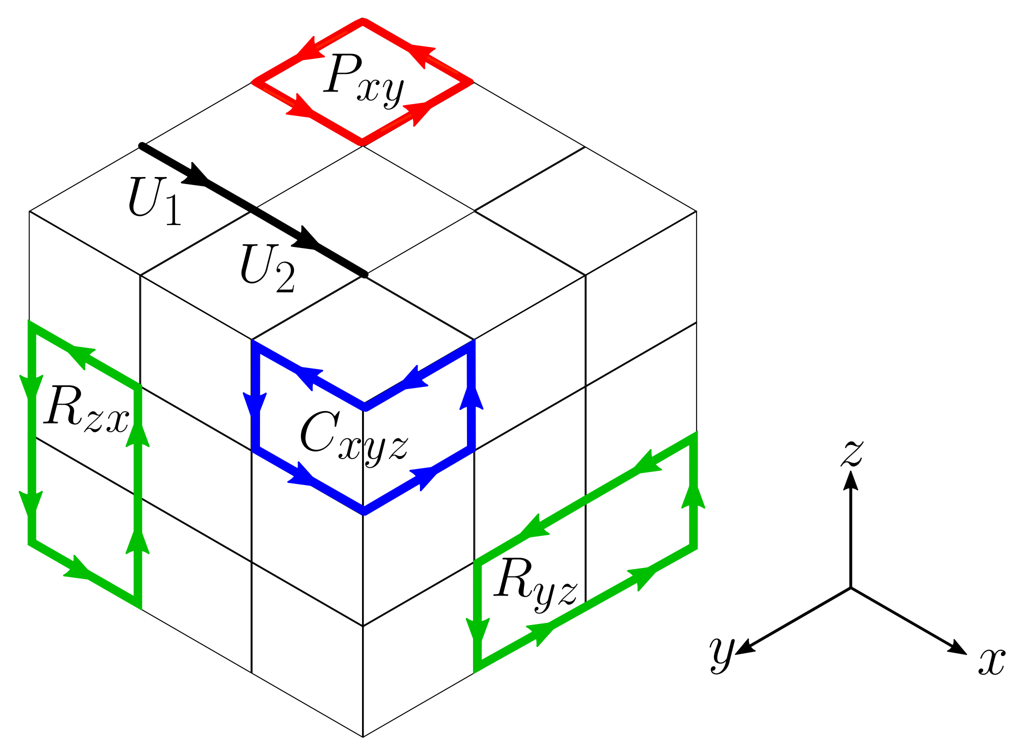
[J. Carlsson, et al, hep-lat/0105018]

$$P_{ij}(x) = 1 - \frac{1}{N}\mathrm{ReTr}\exp\left\{ig\oint_{\square} A\cdot dx\right\} \approx \frac{g^2a^4}{2N}\mathrm{Tr}\left\{F_{ij}(x)F_{ij}(x)\right\} + \frac{g^2a^6}{12N}\mathrm{Tr}\left\{F_{ij}(x)(D_i^2+D_j^2)F_{ij}(x)\right\} + \ldots$$

deviations from the continuum start from a^2 error, classical computational resources proportional a^{-k} to for Wilson action

$$R_{ij}(x) = 1 - \frac{1}{N}\mathrm{ReTr}\left\{\underset{i}{\square\square}\, j\right\} = \frac{4g^2a^4}{2N}\mathrm{Tr}\left\{F_{ij}(x)F_{ij}(x)\right\} + \frac{4g^2a^6}{24N}\mathrm{Tr}\left\{F_{ij}(x)(4D_i^2+D_j^2)F_{ij}(x)\right\} + \ldots$$

deviations from the continuum starts from a^2g^2 at quantum level



Discretization 

$$H_I = K_I + V_I$$

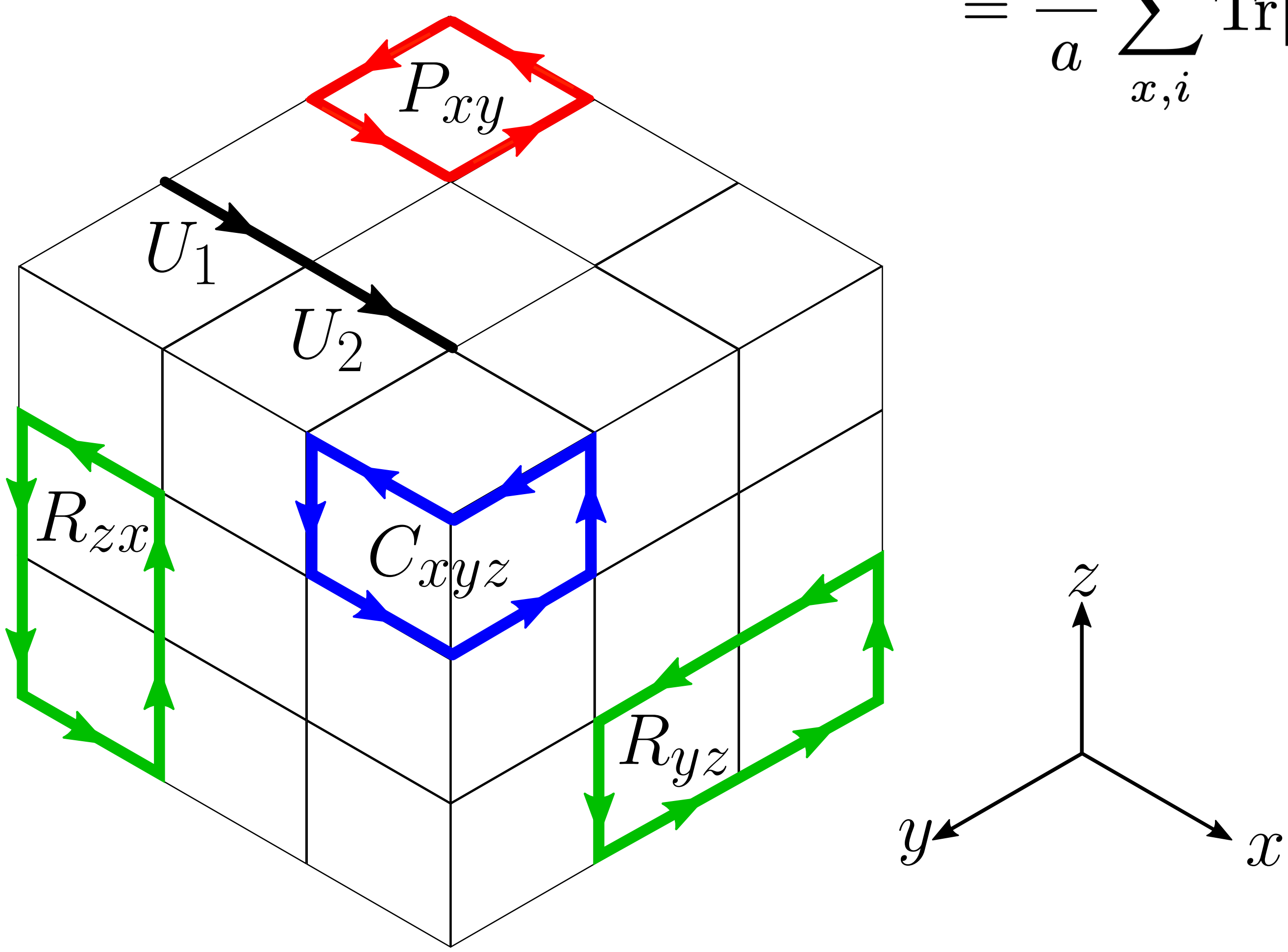
$$V_I = \beta_{V0} V_{KS} + \beta_{V1} V_{\rm rect}\,.$$

$$K_I = \beta_{K0} K_{KS} + \beta_{K1} K_{2L}$$

$$V_{\rm rect} = \frac{2}{a g_s^2} \sum_{\mathbf{x}, i<j} {\rm Re\,Tr}\left[R_{ij}(\mathbf{x}) + R_{ji}(\mathbf{x})\right]$$

$$K_{2L} = \frac{g_t^2}{a} \sum_{\mathbf{x}, i} {\rm Tr}\left[L_i(\mathbf{x}) U_i(\mathbf{x}) L_i(\mathbf{x} + a\mathbf{i}) U_i^\dagger(\mathbf{x})\right]$$

$$= \frac{g_t^2}{a} \sum_{x, i} {\rm Tr}[R_i(\mathbf{x}) L_i(\mathbf{x} + a\mathbf{i})]$$



[M. Alford, et al, hep-lat/9507010, …]

$$a \to 2a$$

$$N_q \sim \left(\frac{L}{a}\right)^d$$

[Demonstration with the improved Hamiltonian is still needed]

[M. Carena, H. Lamm, **YYL**, W. Liu, PRL. **129**, 051601]

Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D **11**, 395 (1975)]

$$H = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2}\sum_\Box \mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)$$

continuous field variables

Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D **11**, 395 (1975)]

$$H = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2}\sum_\Box \mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)$$

continuous field variables

rapid development with its own pros and cons

rate of convergences to the infinite-dimensional theory, resource requirements, local and global gauge symmetry

Casimir dynamics, Natalie et al

LSH formalism, Mathur et al, Anishetty et al

Group-element basis and discrete subgroups, Erez et al, Lamm et al, Carena et al

Magnetic or dual representations, Mathur et al, Bauer et al

Tensor renormalization group (character expansion, Fourier series), Meurice et al

Light-front quantization (light-cone instead of fixed time-slicing), Mannheim et al

Quantum link models/qubit regularization (critical point), Brower et al

Matrix models (dimension reduction), Shen et al

Digitization $|q\rangle^N \rightarrow |G\rangle$

infinities in QFT

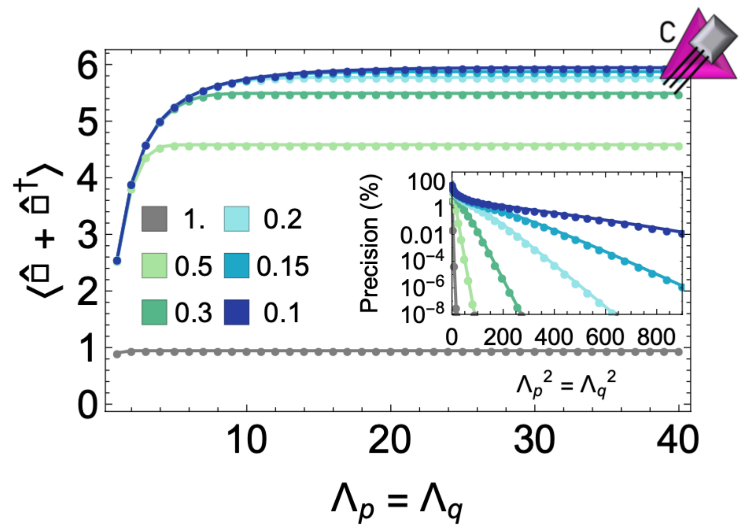
Kogut and Susskind formulation: [Phys. Rev. D **11**, 395 (1975)]

$$H = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2}\sum_\Box \mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)$$

continuous field variables

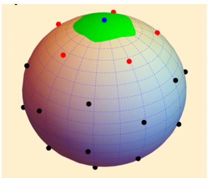
In angular momentum basis,
truncated with cut-off
SU(3) for one plaquette

$$\sum_b |\hat{\mathbf{E}}^{(b)}|^2 |p,q\rangle = \frac{p^2+q^2+pq+3p+3q}{3}|p,q\rangle$$



Ciavarella, Klco, and Savage,
arXiv:2101.10227 [quant-ph]

group element basis -
truncated with discrete subgroup



$\xi_{1-\mathrm{loop}}$	ξ	
	$\mathbb{BI}$	$SU(2)$ [111]
2.097	2.099(1)	⋯
4.278	⋯	4.35(19)
4.207	⋯	4.22(11)
1.351	1.369(19)	⋯
4.136	⋯	4.08(9)
1.351	1.36(1)	⋯

Carena, Gustafson, Lamm,
YYL, Liu, PRD **106**, 114504 (2022)

Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D **11**, 395 (1975)]

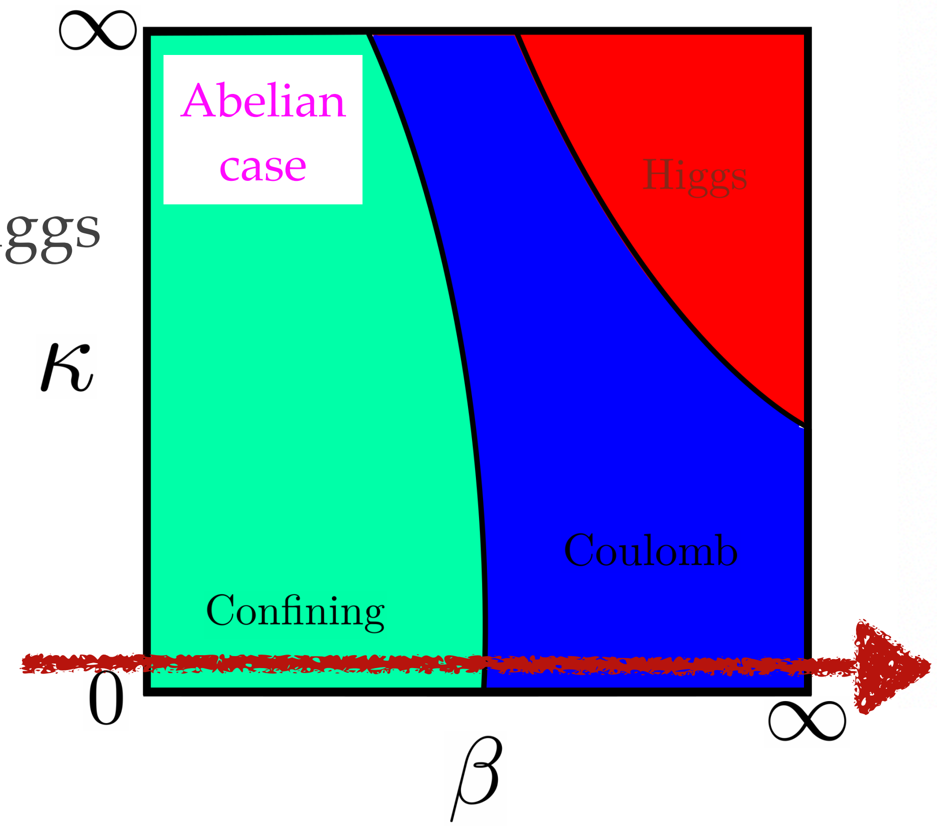
$$H = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x\psi_x^\dagger\psi_x + \frac{g^2}{2}\sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2}\sum_\Box \mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)$$

continuous field variables

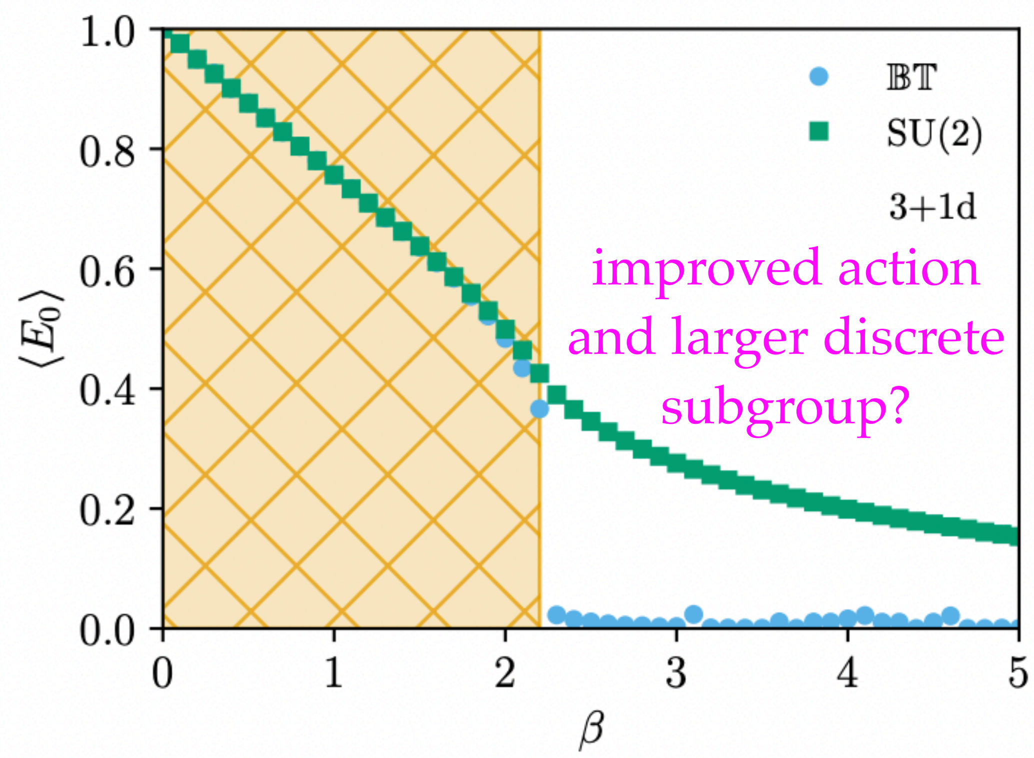
Gauge field truncations with discrete group

discrete group: continuous group + Higgs

For non-Abelian gauge symmetry?



[Fradkin, Shenker, PRD. 19. 3682]



[Erik J. Gustafson et al., arXiv: 2208.12309]

Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D **11**, 395 (1975)]

$$H = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2}\sum_{\square}\mathrm{Tr}\left(U_\square + U_\square^\dagger\right)$$

continuous field variables

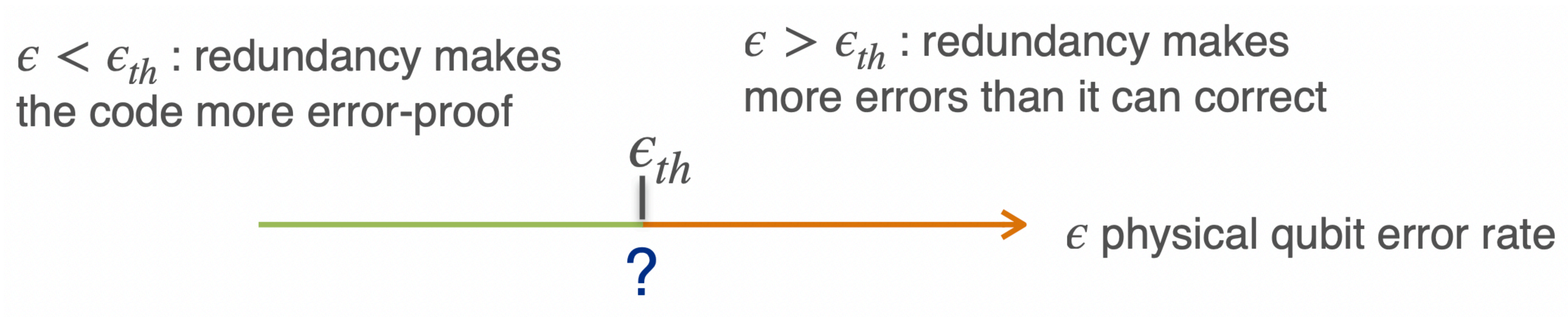
Gauss's law operator

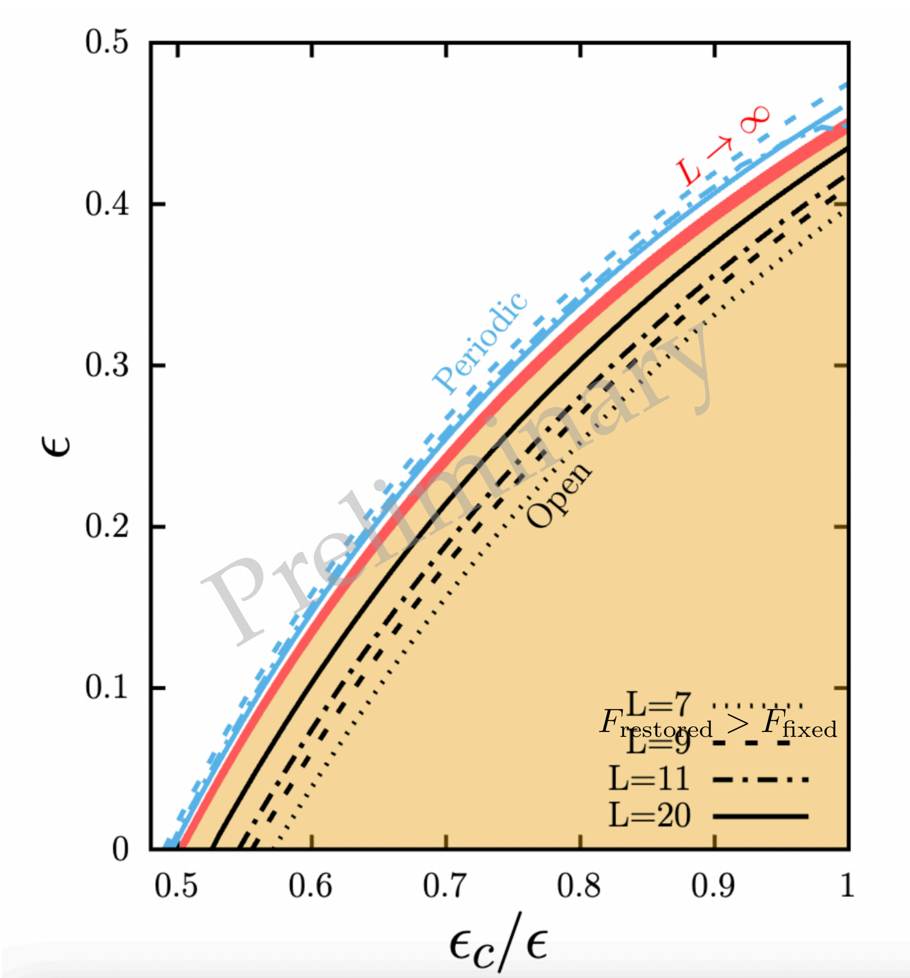
$$G^a(x) = -E_L^a(x) + E_R^a(x-1) + \psi^\dagger(x)T^a\psi(x)$$

$$G_x^a\,|P\rangle = 0$$

Digitization $|q\rangle^N \to |G\rangle$

Gauss's law operator $G^a(x) = -E^a_L(x) + E^a_R(x-1) + \psi^\dagger(x)T^a\psi(x)$ $\quad G^a_x\,|P\rangle = 0$





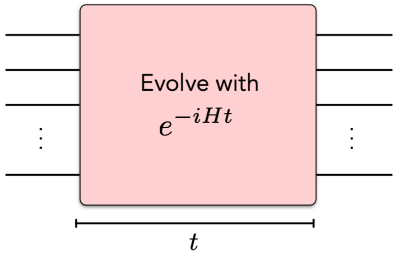
gauge redundancy: resilience to quantum errors

[M. Carena, H. Lamm, **YYL**, W. Liu, in preparation]

Gauge symmetry used for error corrections, see Halimeh, et al. Lamm, et al. …

Propagation $\mathcal{U}\,|\psi_0\rangle \rightarrow |\psi(t)\rangle$

ANALOG



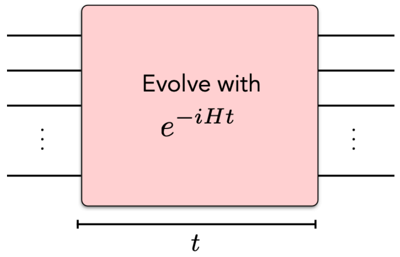
Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics

Superconducting circuits

...

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

ANALOG



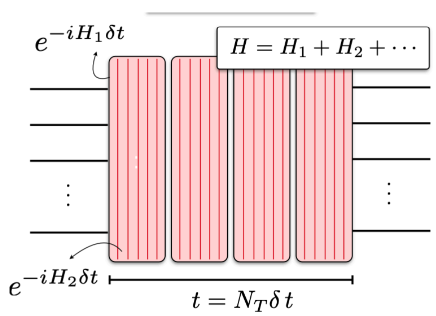
Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics

Superconducting circuits

...

DIGITAL

superconducting qubit/trapped-ion system



building blocks:

one-qubit/two-qubit gate set

$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

optimal asymptotically?

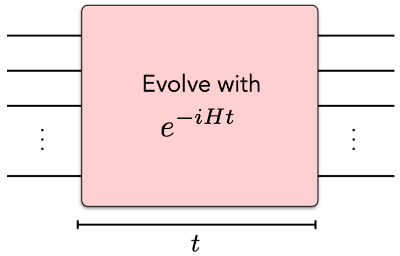
overload of resources?

easy implementation?

[Bauer et al, arXiv:2204.03381]

Propagation $\mathcal{U}\,|\psi_0\rangle \rightarrow |\psi(t)\rangle$

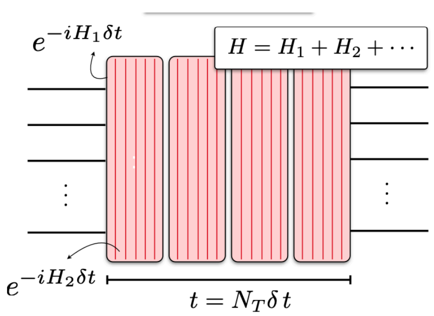
ANALOG



Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits
…

DIGITAL

superconducting qubit / trapped-ion system



building blocks:
one-qubit / two-qubit gate set

$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

optimal asymptotically?
overload of resources?
easy implementation?

Trotter-Suzuki decomposition

$$H = \sum_{l=1}^{\Gamma} H^{(l)}$$

$$\mathcal{U} = \left[\prod_{l=1}^{\Gamma} e^{-itH^{(l)}/r}\right]^r$$

p-th order trotterization: $\mathcal{O}\left((\frac{t}{r})^p\right)$

Errors depends on t and r
No ancillary overhead
Simpler implementation

Taylor series expansion (LCU)

$$e^{-iHt} = (e^{-iHt/r})^r \equiv V^r$$

$$V \approx \tilde{V} = \sum_{k=0}^{K} \frac{1}{k!}(\frac{-iHt}{r})^k$$

$$\mathcal{U} = \tilde{V}^r$$

$$||\tilde{V} - V|| < \epsilon/r$$

K values depends on the aimed errors
Ancillary qubits are needed
Complex circuits implementation

Quantum singular value transformation

$$e^{-iHt} = \cos(Ht) - i\sin(Ht)$$

$$e^{i\phi_0\sigma_z}\prod_{j=1}^{k}\left(W(x)e^{i\phi_j\sigma_z}\right) = \begin{bmatrix} P(x) & iQ(x)\sqrt{1-x^2} \\ iQ^*(x)\sqrt{1-x^2} & P^*(x) \end{bmatrix}$$

$$W(x) := \begin{bmatrix} x & i\sqrt{1-x^2} \\ i\sqrt{1-x^2} & x \end{bmatrix}$$

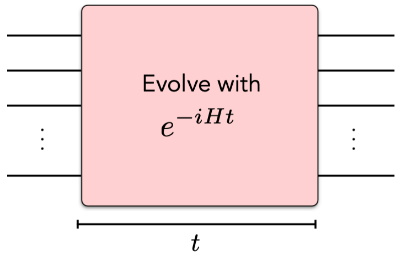
Jacobi-Anger expansion for cos and sin

error: truncation order of the expansion
Ancillary qubits are needed
Complex circuits implementation

Quantum signal processing, blocking encoding, off-diagonal Hamiltonian expansion, etc… *PRX Quantum* 4 (2023) 2, 027001

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

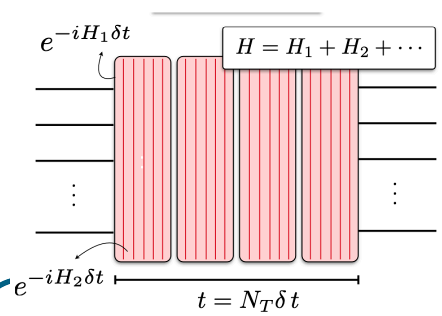
ANALOG



Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits
…

DIGITAL

superconducting qubit / trapped-ion system



building blocks:
one-qubit / two-qubit gate set

$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

optimal asymptotically?
overload of resources?
easy implementation?

HYBRID METHOD

Casanova et al (2011), Davoudi et al (2021) [trapped ion]

Harmalkar et al (2022) classical preprocessing

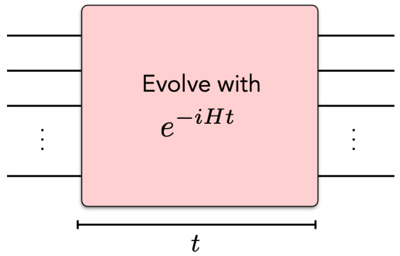
Zohar et al (2017), Bender et al (2018) effective interactions

Klco et al (2018), Kokail et al (2019), Atas et al (2021) state preparations

Peruzzo et al (2014), Farhi et al (2014) optimization methods

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

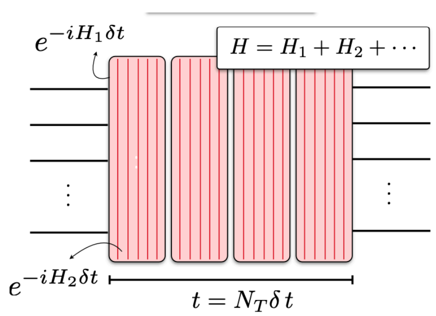
ANALOG



Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits
…

DIGITAL

superconducting qubit / trapped-ion system



building blocks:
one-qubit / two-qubit gate set

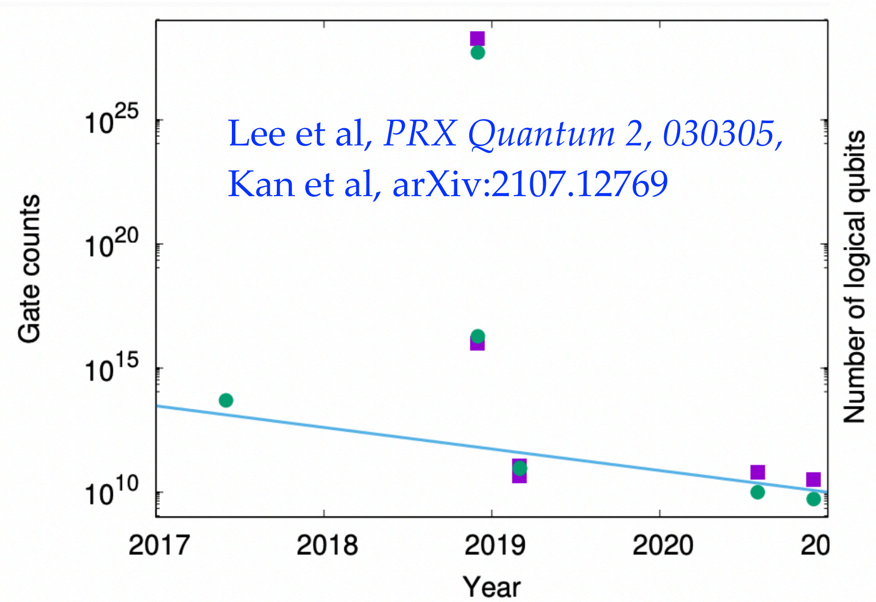
$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

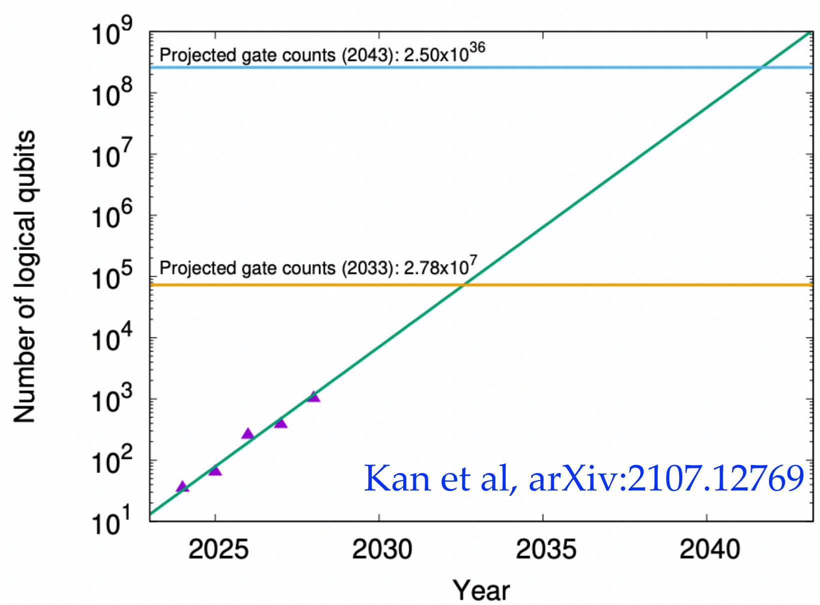
Trotter-Suzuki decomposition

$$H = \sum_{l=1}^{\Gamma} H^{(l)}$$

$$\mathcal{U} = \left[\prod_{l=1}^{\Gamma} e^{-itH^{(l)}/r}\right]^r$$

RESOURCE ESTIMATION AND CIRCUITS CONSTRUCTION IMPROVEMENT





heavy ion collision

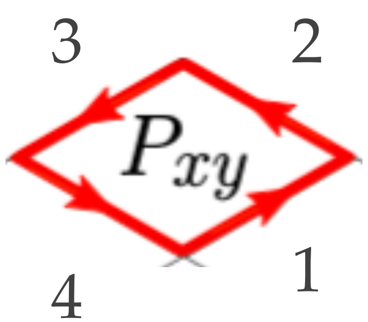
Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

$$\mathcal{U}(t) = e^{-iH_{KS}t}$$
$$\approx \left[e^{-i\delta t K_{KS}}e^{-i\delta t V_{KS}}\right]^{t/\delta t}$$

$$K_{KS} = \sum_{\mathbf{x},i} \frac{g_t^2}{a}\,\mathrm{Tr}\,L_i^2(\mathbf{x})$$

$$V_{KS} = -\sum_{\mathbf{x},i<j} \frac{2}{g_s^2 a}\,\mathrm{Re}\,\mathrm{Tr}\,P_{ij}(\mathbf{x})$$

$$P_{ij}(x) = 1 - \frac{1}{N}\mathrm{ReTr}\left\{\Box_{i}^{j}\right\}$$



$$\mathrm{Tr}\{U_1U_2U_3^\dagger U_4^\dagger\}$$

General Method

[H. Lamm, et al, arXiv:1903.08807]

$G-$register : $|g\rangle$

$$\mathfrak{U}_\times\,|g\rangle\,|h\rangle = |g\rangle\,|gh\rangle$$

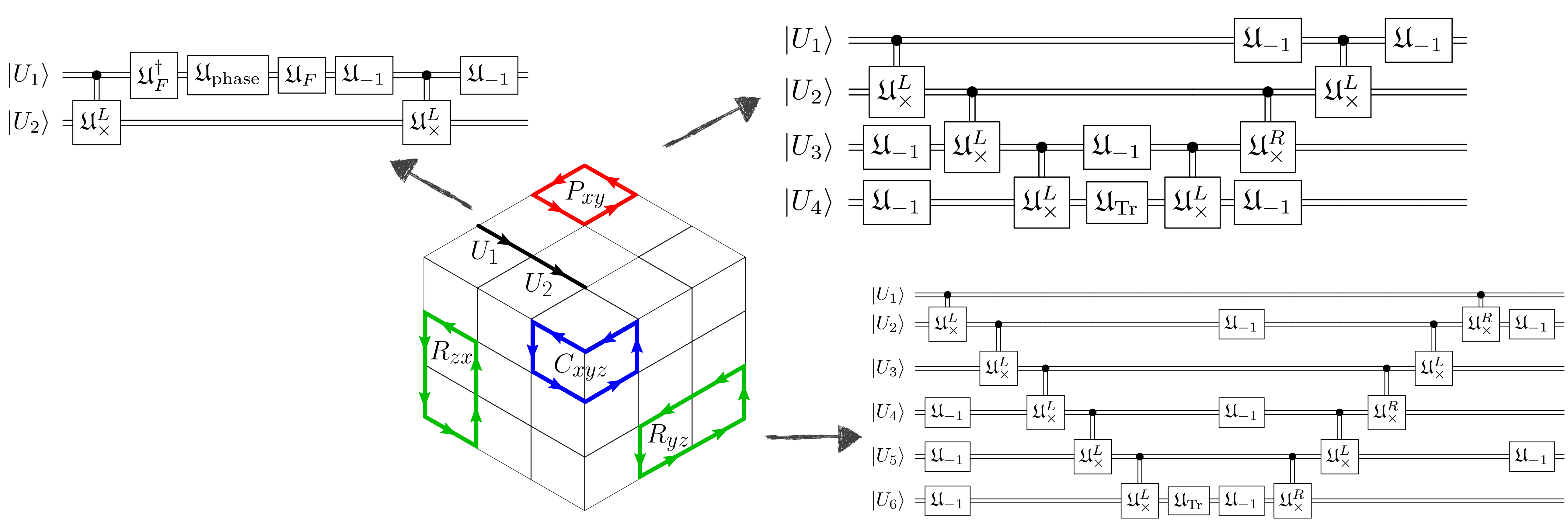
$$\mathfrak{U}_{-1}\,|g\rangle = \left|g^{-1}\right\rangle$$

$$\mathfrak{U}_{\mathrm{Tr}}(\theta)\,|g\rangle = e^{i\theta\,\mathrm{Re\,Tr}\,g}\,|g\rangle$$

$$\mathfrak{U}_F \sum_{g\in G} f(g)\,|g\rangle = \sum_{\rho\in\hat{G}} \hat{f}(\rho)_{ij}\,|\rho,i,j\rangle$$

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

$$H_I = K_I + V_I$$
$$V_I = \beta_{V0} V_{KS} + \beta_{V1} V_{\text{rect}}\, .$$
$$K_I = \beta_{K0} K_{KS} + \beta_{K1} K_{2L}$$



[M. Carena, H. Lamm, **YYL**, W. Liu, PRL. **129**, 051601]

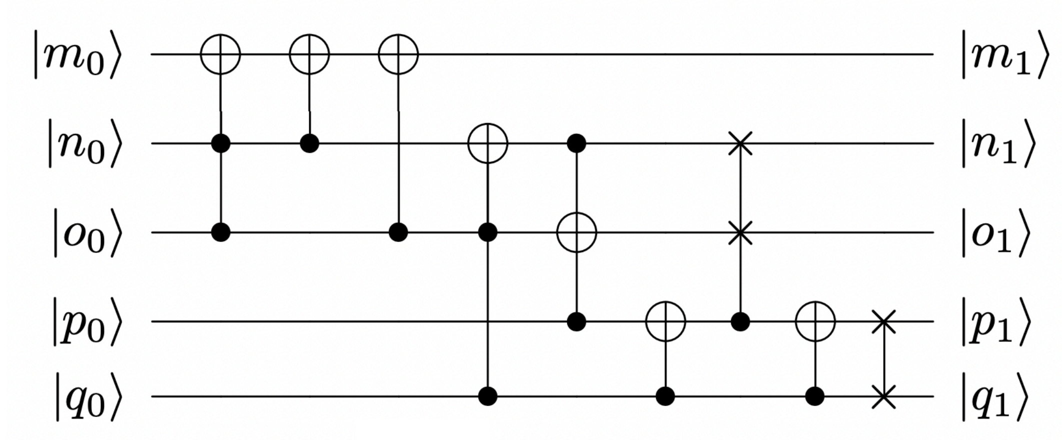
Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

[Erik J. Gustafson et al., arXiv: 2208.12309]

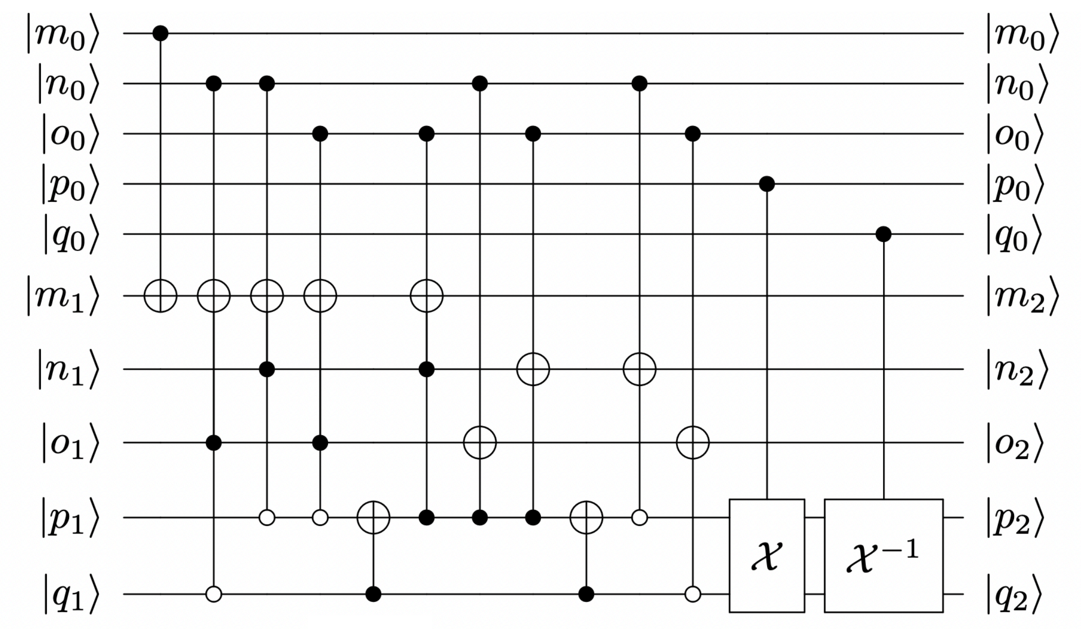
BT discrete group
with 24 group elements

$$g = (-1)^m \mathbf{i}^n \mathbf{j}^o \mathbf{l}^{p+2q}$$

$$|qponm\rangle$$



$\mathfrak{U}_{-1} : U_0 \to U_0^\dagger$



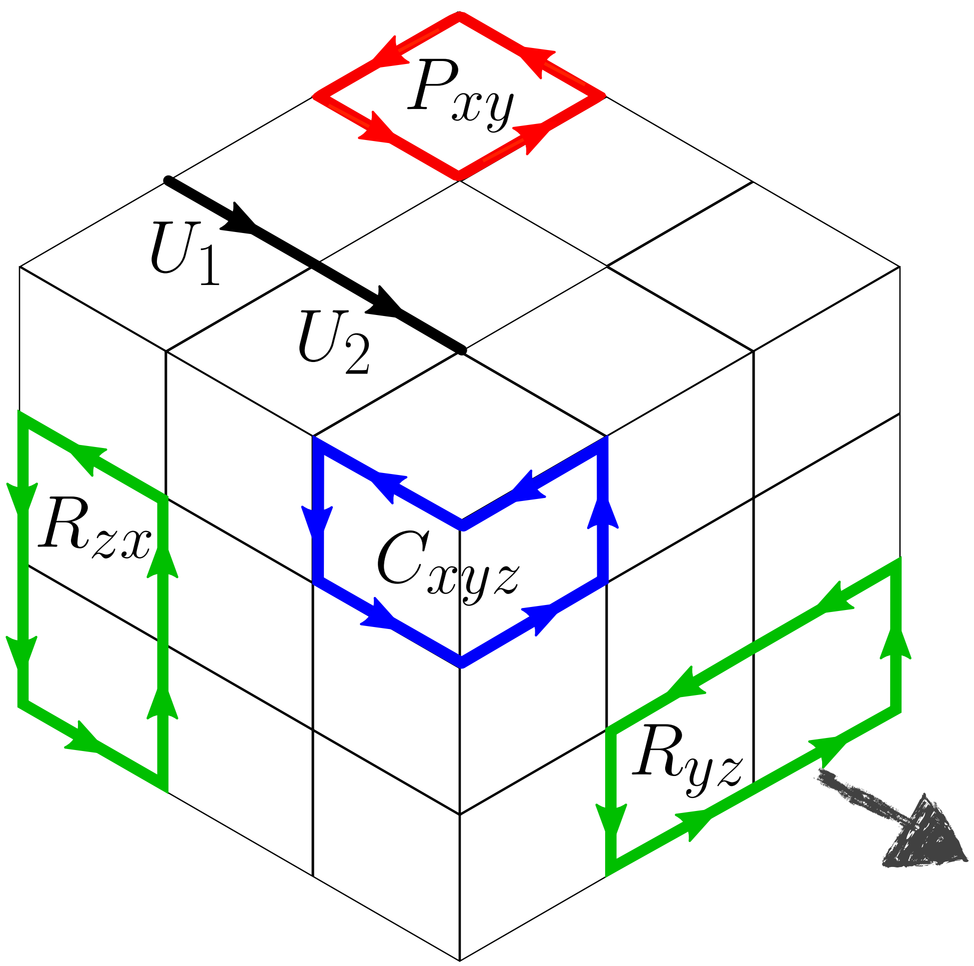
$\mathfrak{U}_\times : U_3 U_0 \to U_3 U_0'$

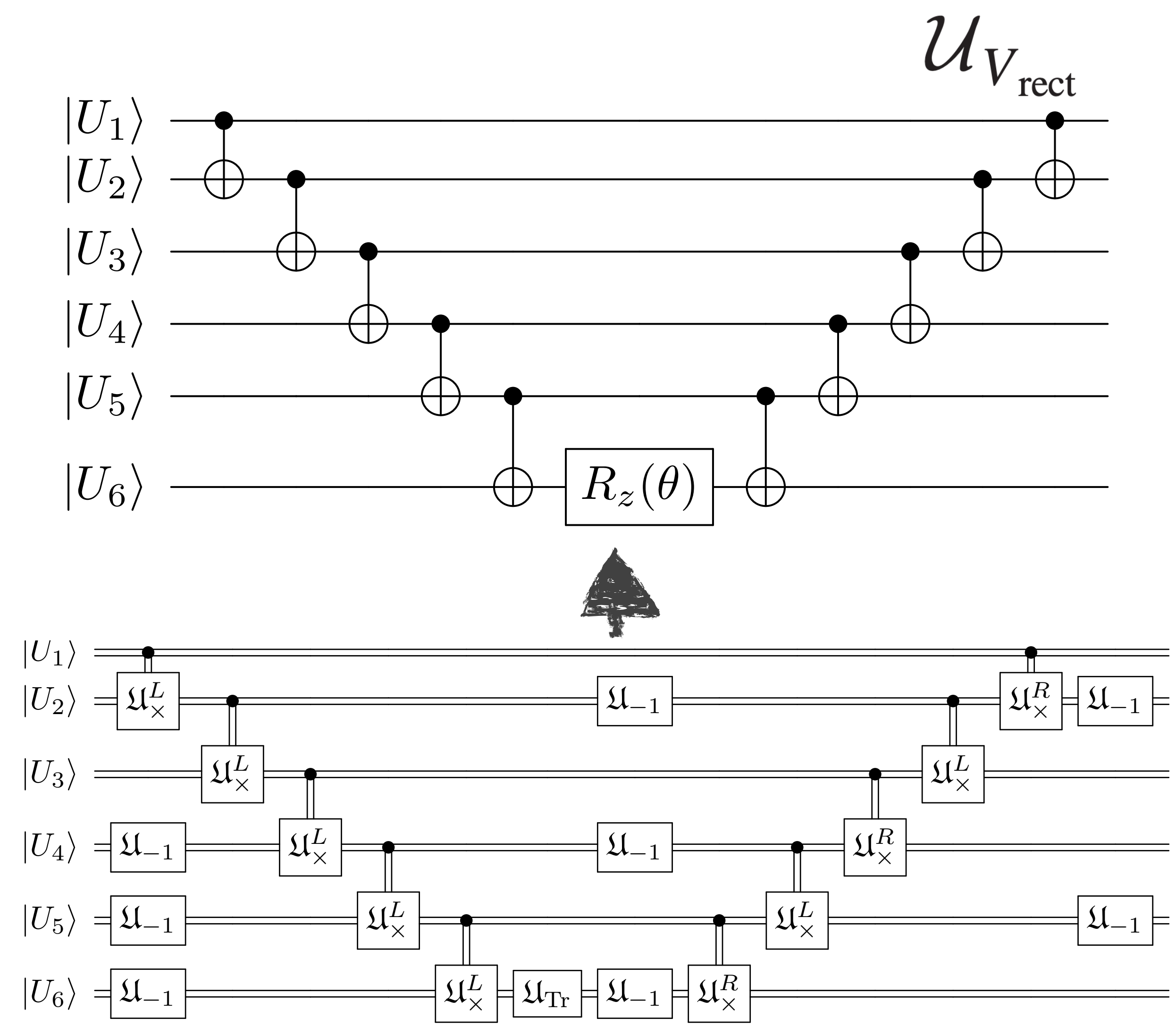
$\mathfrak{U}_F$:~1000 CNOT gates

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

$$\mathbb{Z}_2 \qquad 1 \to |0\rangle \qquad -1 \to |1\rangle$$

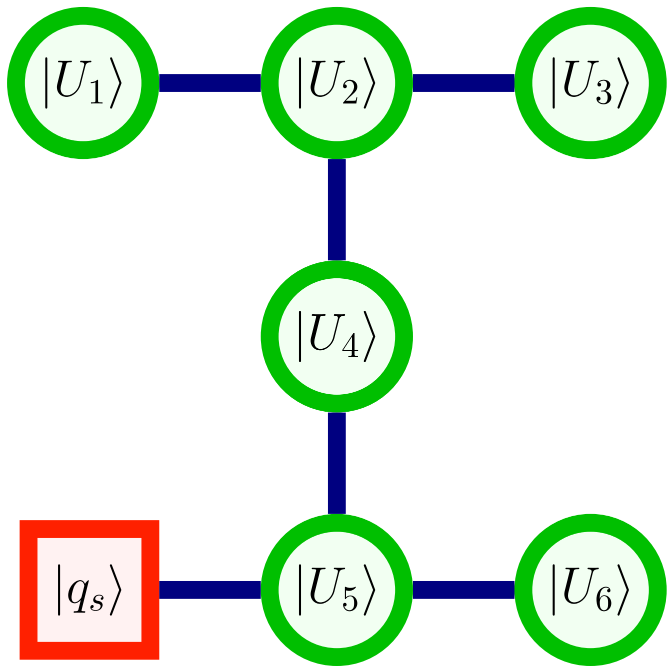
$\mathfrak{U}_F$	H
$\mathfrak{U}_{\text{phase}}$	$R_z(\theta)$
$\mathfrak{U}_{\text{Tr}}$	$R_z(\theta)$
$\mathfrak{U}_{-1}$	$\mathbb{1}$
$\mathfrak{U}_{\times}$	CNOT



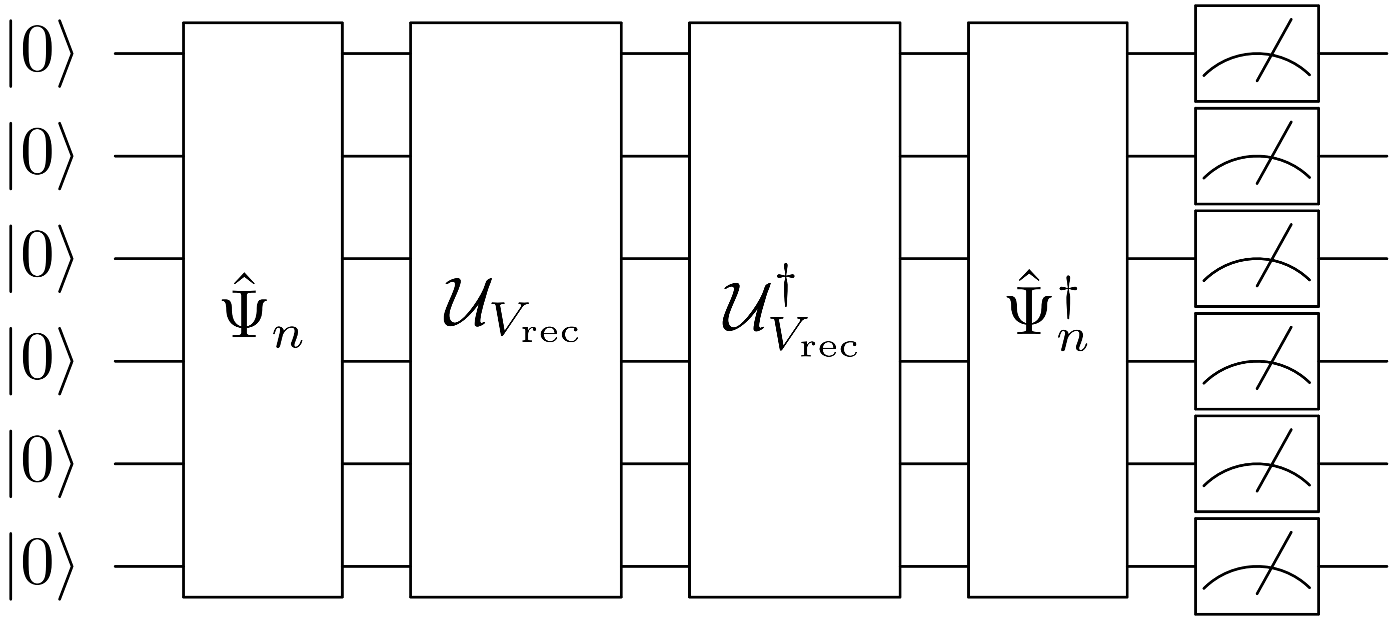


[M. Carena, H. Lamm, **YYL**, W. Liu, PRL. **129**, 051601]

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$



ibm_perth device



$$\hat{\Psi}_n = \prod_{m\leq n} H_m^{\otimes}$$

$$\left[\prod_i (\sigma_i^{b_i})^{\otimes}\right] \mathrm{CNOT} \otimes \mathbb{1}_4 \left[\prod_i (\sigma_i^{a_i})^{\otimes}\right] = \mathrm{CNOT} \otimes \mathbb{1}_4$$

$$\mathcal{F}_{\rm rect} = 0.550 \qquad \mathcal{F}_\delta \approx 0.25$$

demonstration of improved Hamiltonian is allowed in the near future

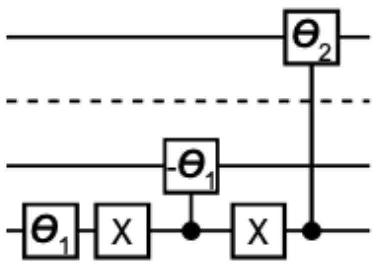
[M. Carena, H. Lamm, **YYL**, W. Liu, PRL. **129**, 051601]

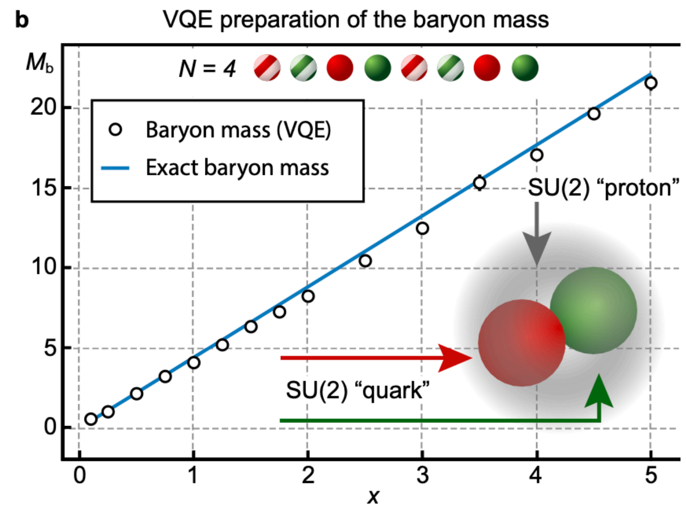
To reach the observables — How to do …

INITIAL STATE PREP

hadronic state, topological vacuum state, thermal state, etc

Hybrid methods with VQE protocols



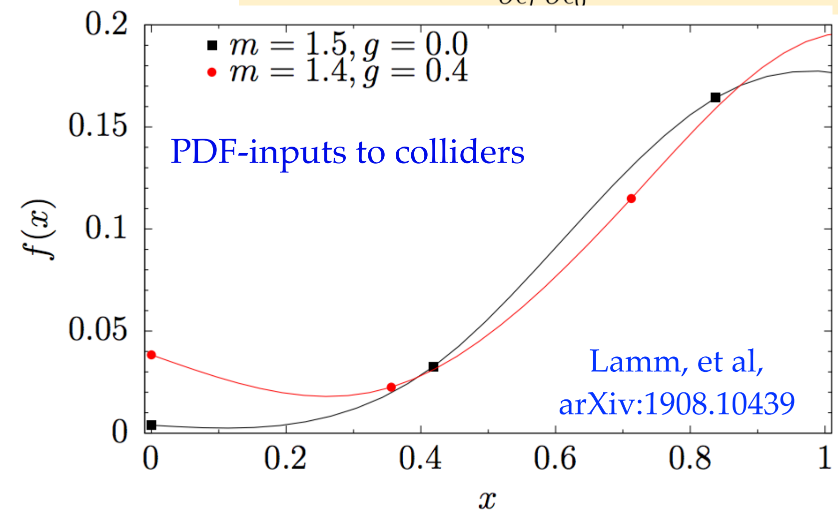


Atas et al, Nat Commun 12, 6499 (2021)

MEASUREMENTS

time-separated correlators, exponentially suppressed process, entanglement, etc

$$\langle\Psi|\mathcal{O}(t)\mathcal{O}(0)|\Psi\rangle = \frac{\partial}{\partial\epsilon_t}\frac{\partial}{\partial\epsilon_0}\langle\Psi|e^{-iHt}e^{-i\mathcal{O}\epsilon_t}e^{iHt}e^{i\mathcal{O}\epsilon_0}|\Psi\rangle$$

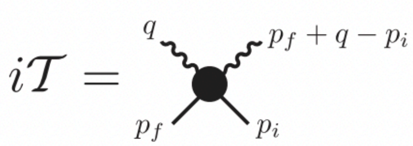


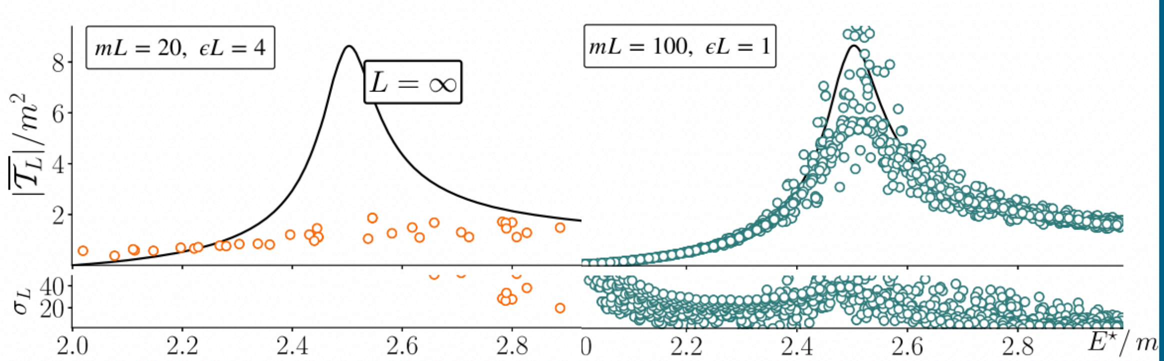
T. Li, et al, arXiv:2207.13258

…

SYSTEMATIC UNCERTAINTIES

finite volume effects, truncation errors, convergence rate



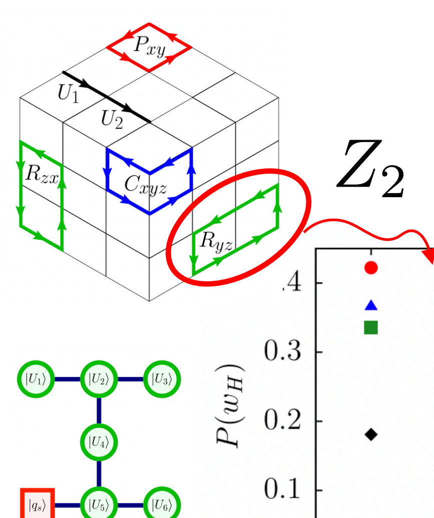


Briceno, PRD 103, 014506 (2021)

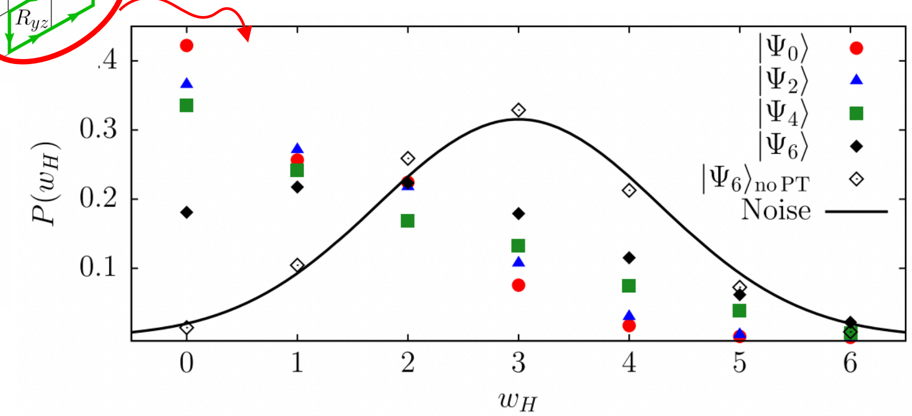
ERROR CORRECTIONS

gate error - stochastic and coherent errors

readout errors



$$Z_2 \quad \left[\prod_i (\sigma_i^{b_i})^{\otimes}\right] \mathrm{CNOT}\otimes\mathbb{1}_4 \left[\prod_i (\sigma_i^{a_i})^{\otimes}\right] = \mathrm{CNOT}\otimes\mathbb{1}_4$$

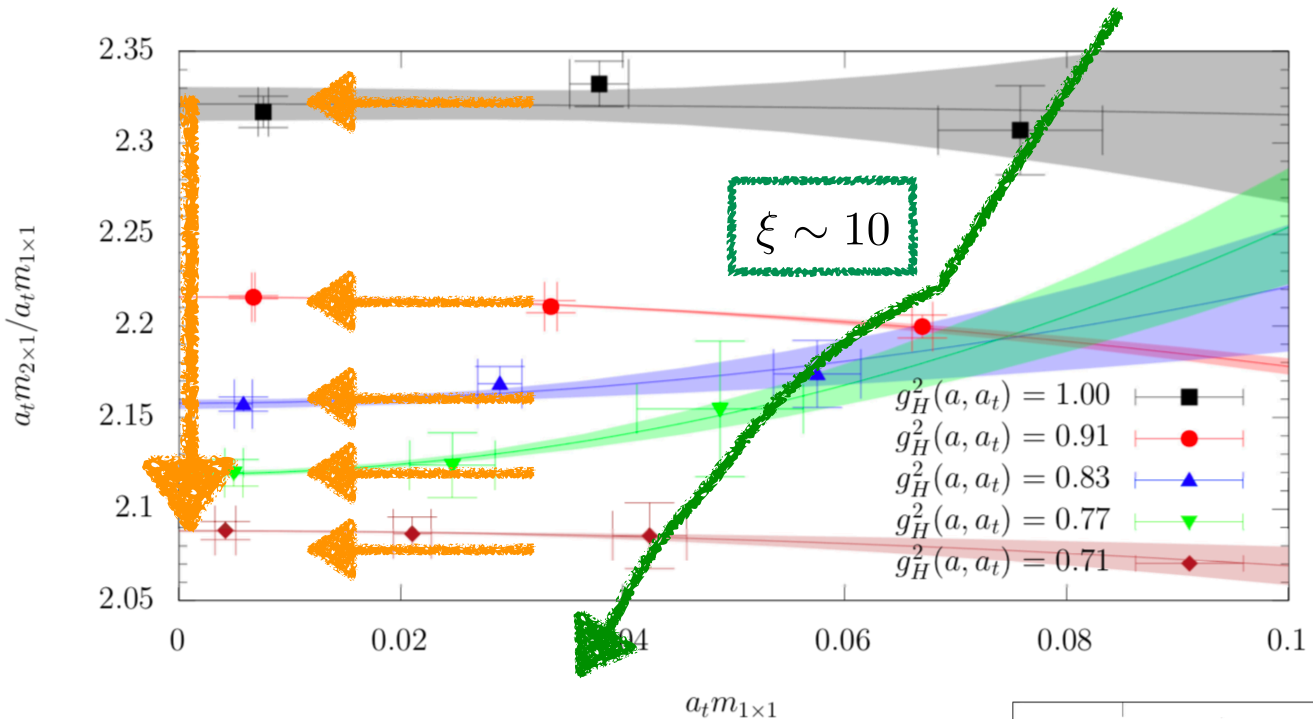


Carena, Lamm, **YYL**, Liu, PRL. **129**, 051601

To reach observables in the continuum limit

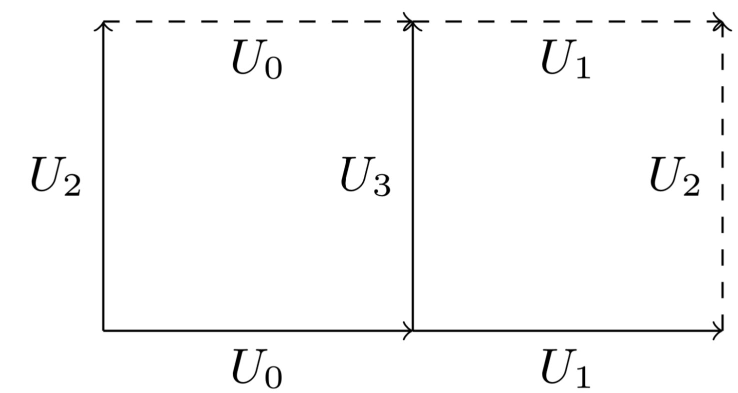
TRAJECTORY TO THE CONTINUUM LIMIT

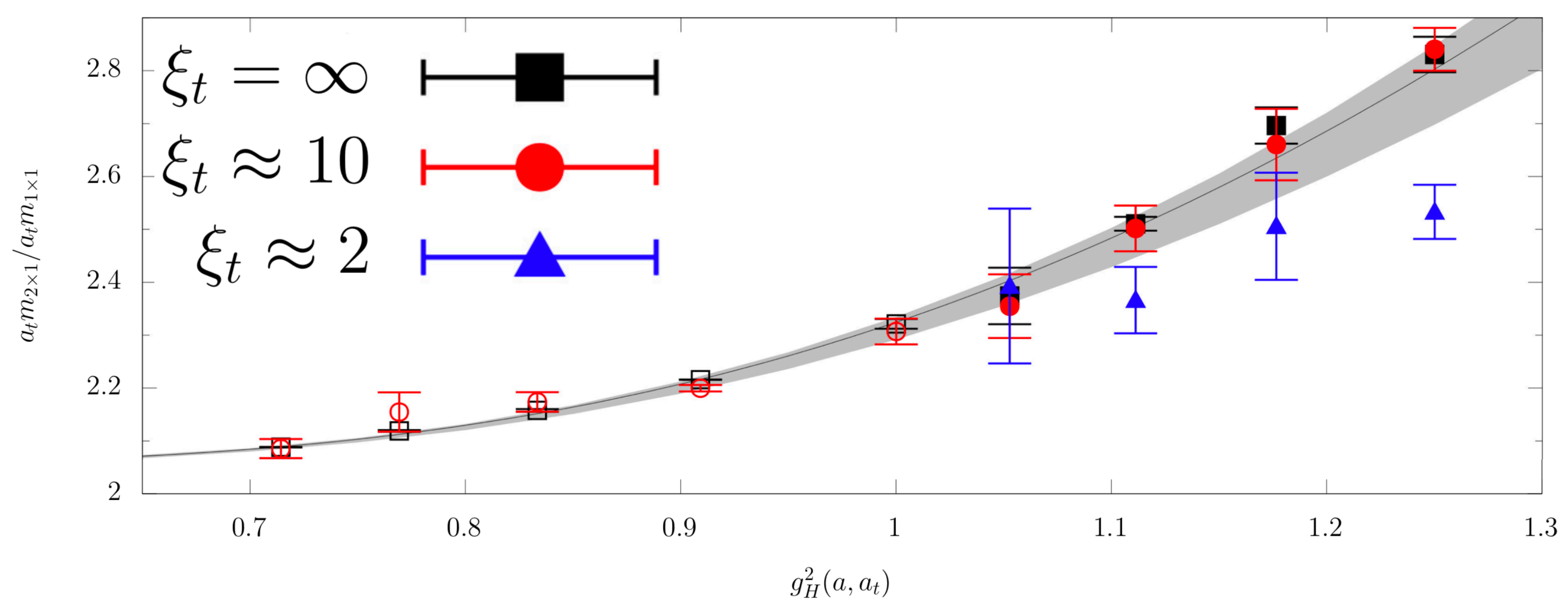
continuum limit: extrapolation to the continuum at $\xi = a/a_t$



[M. Carena, H. Lamm, **YYL**, W. Liu, PRD. **104**, 094519]

D4 group



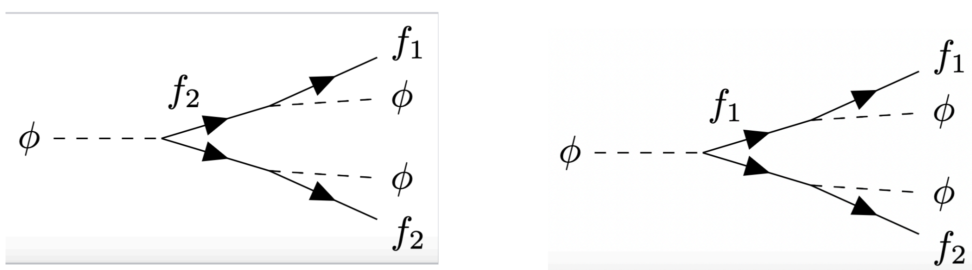


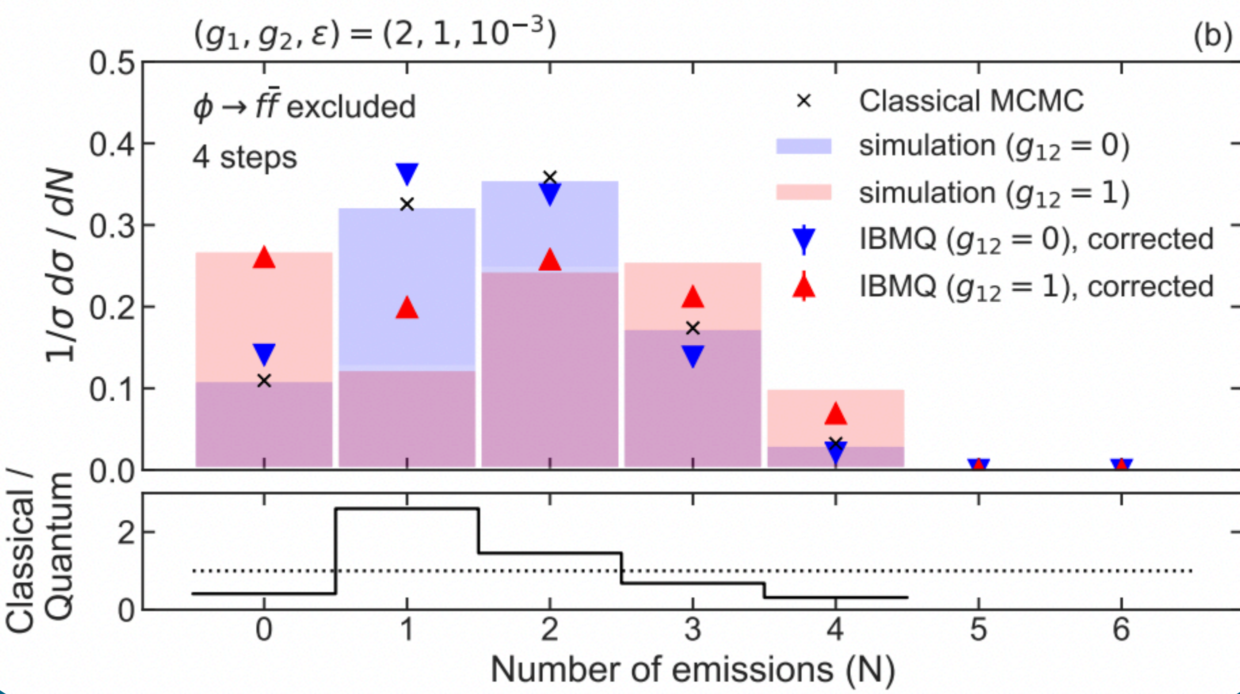
$g_H^2 \propto 1/\log(a) \to 0$

Benchmarks

PARTON SHOWERING [arXiv:2102.05044, PRD 103, 076020, PRD 106, 056002,…]

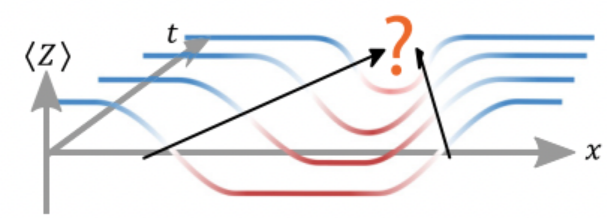
$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2 + g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi$$

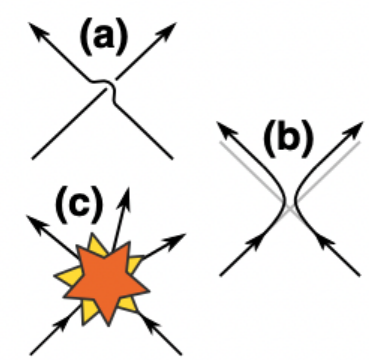


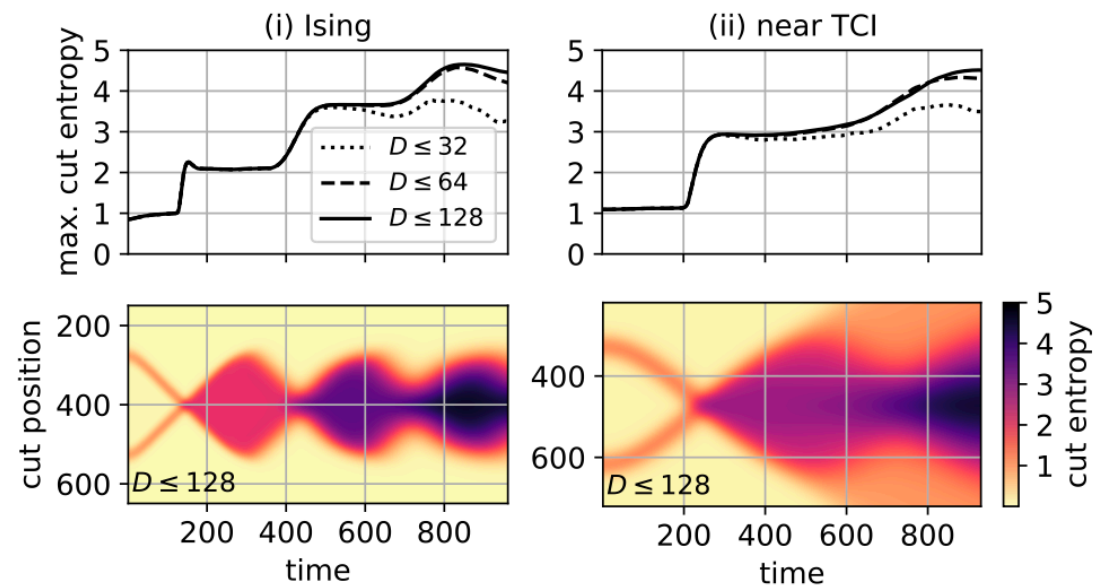


BUBBLE COLLISION

$$H = \sum_{j=1}^{N}[-Z_j Z_{j+1} - gX_j - hZ_j + \lambda(X_j Z_{j+1} Z_{j+2} + Z_j Z_{j+1} X_{j+2})].$$







the maximum cut entropy at $D \le 128$ very likely not converged after $t \approx 700$

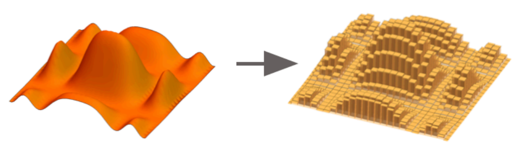
[Milsted, et al, PRXQuantum.3.020316]

“It is time to go”

SUMMARY and OUTLOOK

Quantum computing can access to quantities in high energy physics which are intractable with classical methods

So many things to do, … and lots should be done to before scalable noise-resilient ones are available.

Discretization  *KS Hamiltonian*

Digitization $|q\rangle^N \rightarrow |G\rangle$ *truncation, discrete subgroup, …*

$\downarrow$

Initialization $\mathcal{U}\,|G\rangle^L \rightarrow |\psi_0\rangle$ *ground/thermal/particle state prep*

$\downarrow$

Propagation $\mathcal{U}\,|\psi_0\rangle \rightarrow |\psi(t)\rangle$ *Trotterization, variational approach, Taylor series, …*

$\downarrow$

Evaluation $\langle\mathcal{O}\rangle$ *Parton distribution function, particle decay, …*

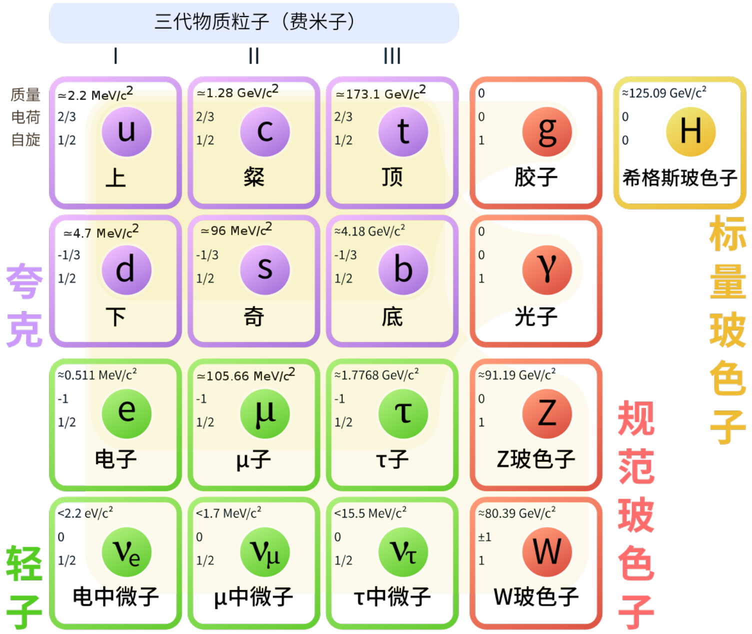
Error mitigation

Theory investigations, algorithmic developments, benchmark study, hardware co-design,…

Thank you

BACK UP

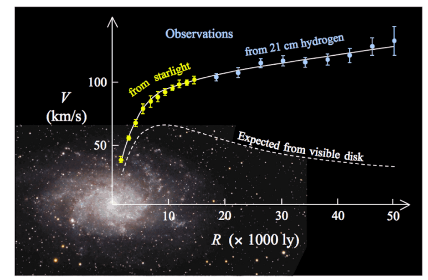
-1973: Standard Model



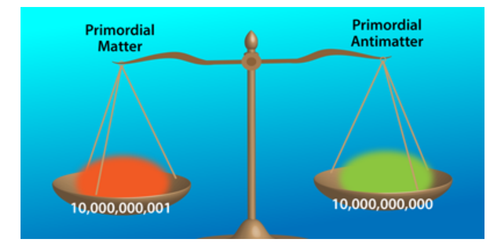
1897-2012:
electron, muon, tau lepton, gluon, W and Z boson,
top quark, tau neutrino, Higgs boson

Puzzles We Encountered

1933-Now
dark matter

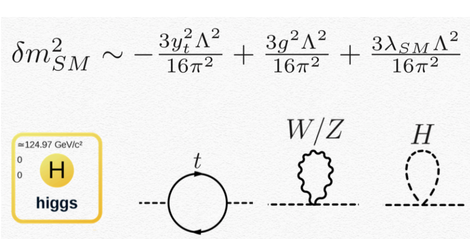


1940s-Now
baryon
asymmetry



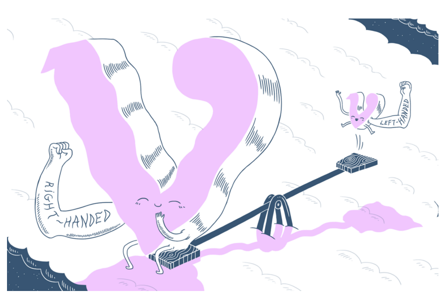
out of equilibrium

1967-Now
naturalness
problem



strong dynamics

1960s-Now
neutrino mass



1960s-Now
Strong CP problem

$$\mathscr{L} \supset -\frac{1}{4}G^2 + \frac{\theta g_s^2}{32\pi^2}G\tilde{G}$$

$$\bar{\theta} \lesssim 10^{-10}$$

CP-violating phase in the CKM matrix is about π/3

complex action

grand unified theory?

…

precision measurement

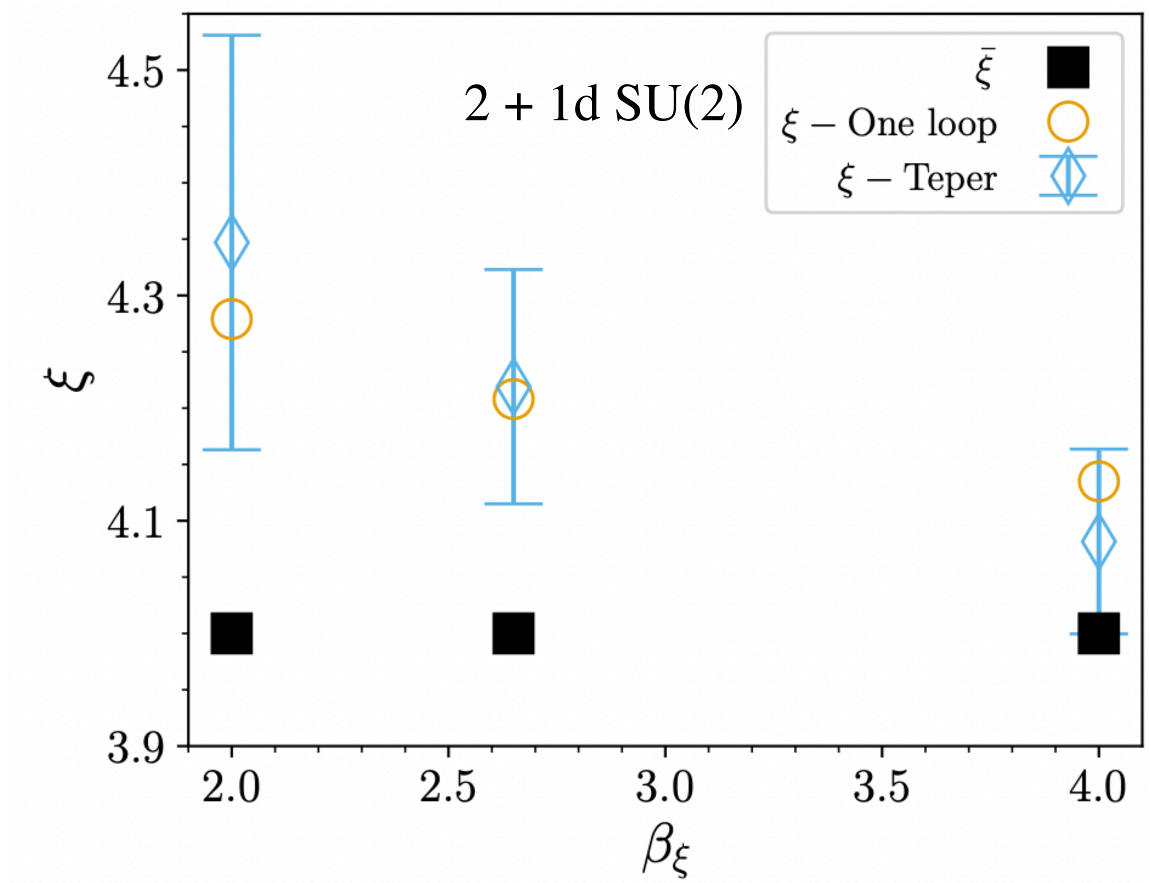
rare events

theoretical inputs to colliders

Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

Anisotropic Parameter $\xi = a/a_t$ *Renormalization*

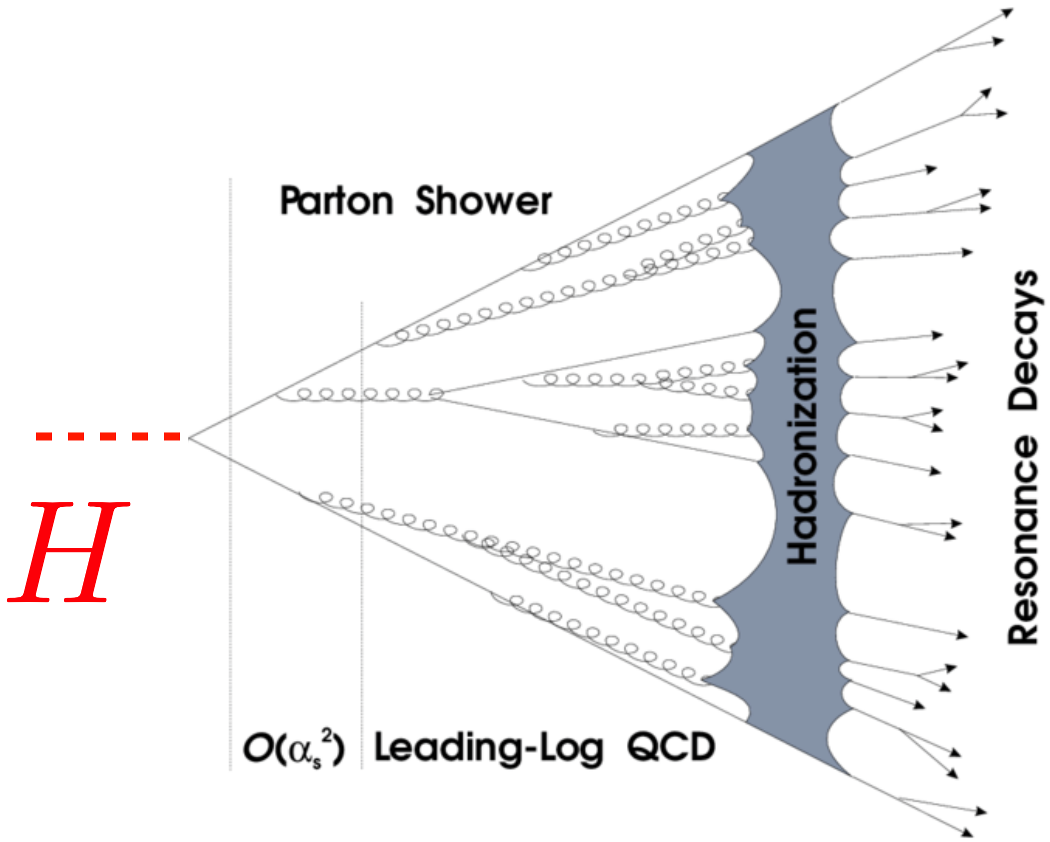
- numerical results is pretty tedious—saving measurement on the Euclidean side
- Preferred for analytical continuation
- Determine the fixed anisotropic trajectory
- Continuous group agrees quite well with their discrete subgroups



β_ξ	N_s	N_t	$\bar{\xi}$	$\xi_{1-\text{loop}}$	ξ	
					$\mathbb{BI}$	$SU(2)$ [111]
$D=3$						
2.00	36	72	2.00	2.097	2.099(1)	⋯
2.00	12[a]	60[a]	4.00	4.278	⋯	4.35(19)
2.65	16[a]	64[a]	4.00	4.207	⋯	4.22(11)
3.00	36	72	1.33	1.351	1.369(19)	⋯
4.00	24[a]	96[a]	4.00	4.136	⋯	4.08(9)
$D=4$						
3.0	36	72	1.33	1.351	1.36(1)	⋯

[M. Carena, E. Gustafson, H. Lamm, **YYL**, W. Liu, PRD 106 11, 114504]

Theoretical inputs to colliders



Parton Shower

Long-distance dynamics - dominated by massless modes, high multiplicity final states

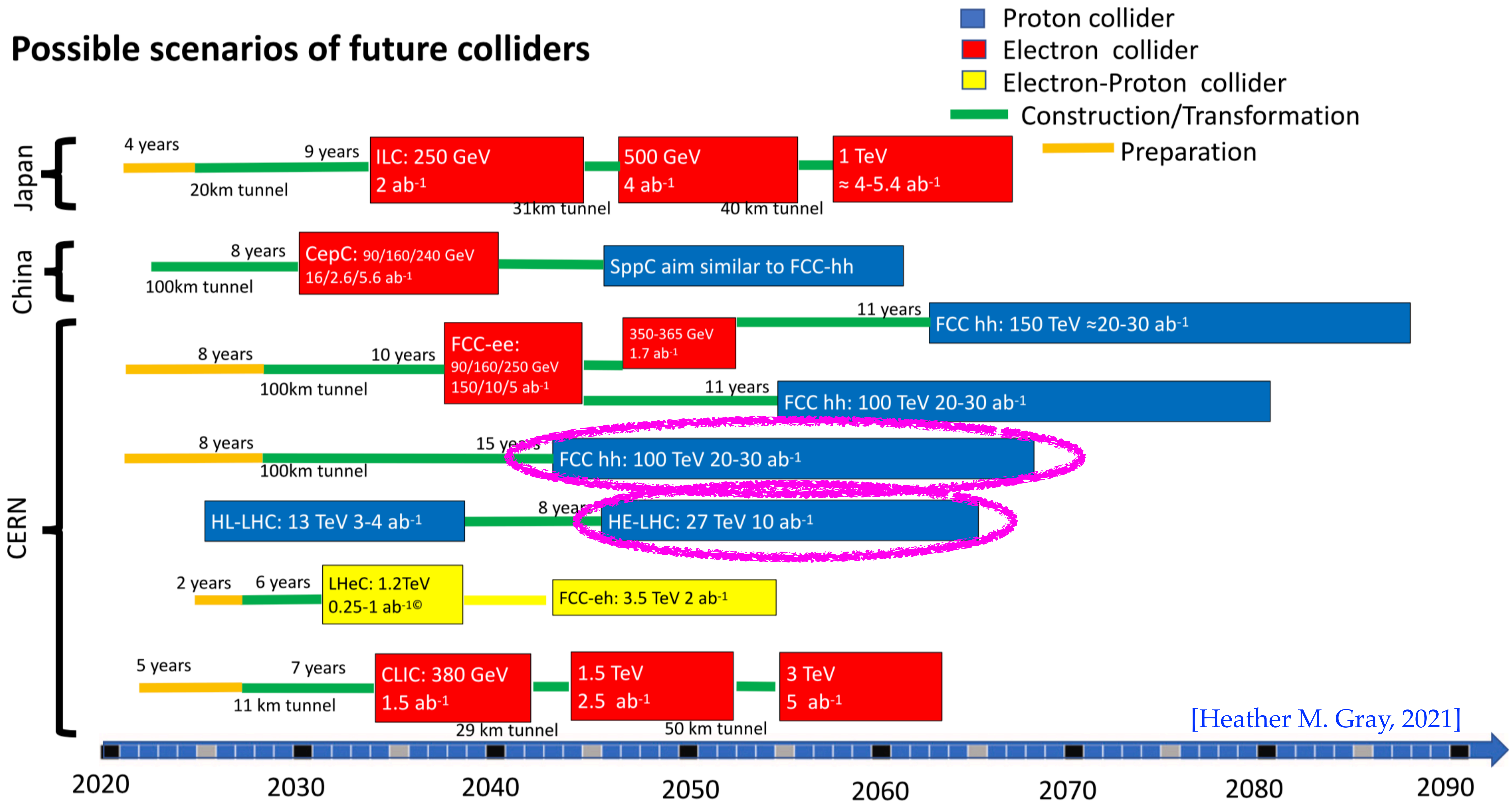
$$\sigma = H \otimes J_1 \otimes \cdots \otimes J_n \otimes S$$

collinear **soft**

Lattice: in principle, sign problem
State-of-art tech (MCMC):
probability level—interference
not properly included

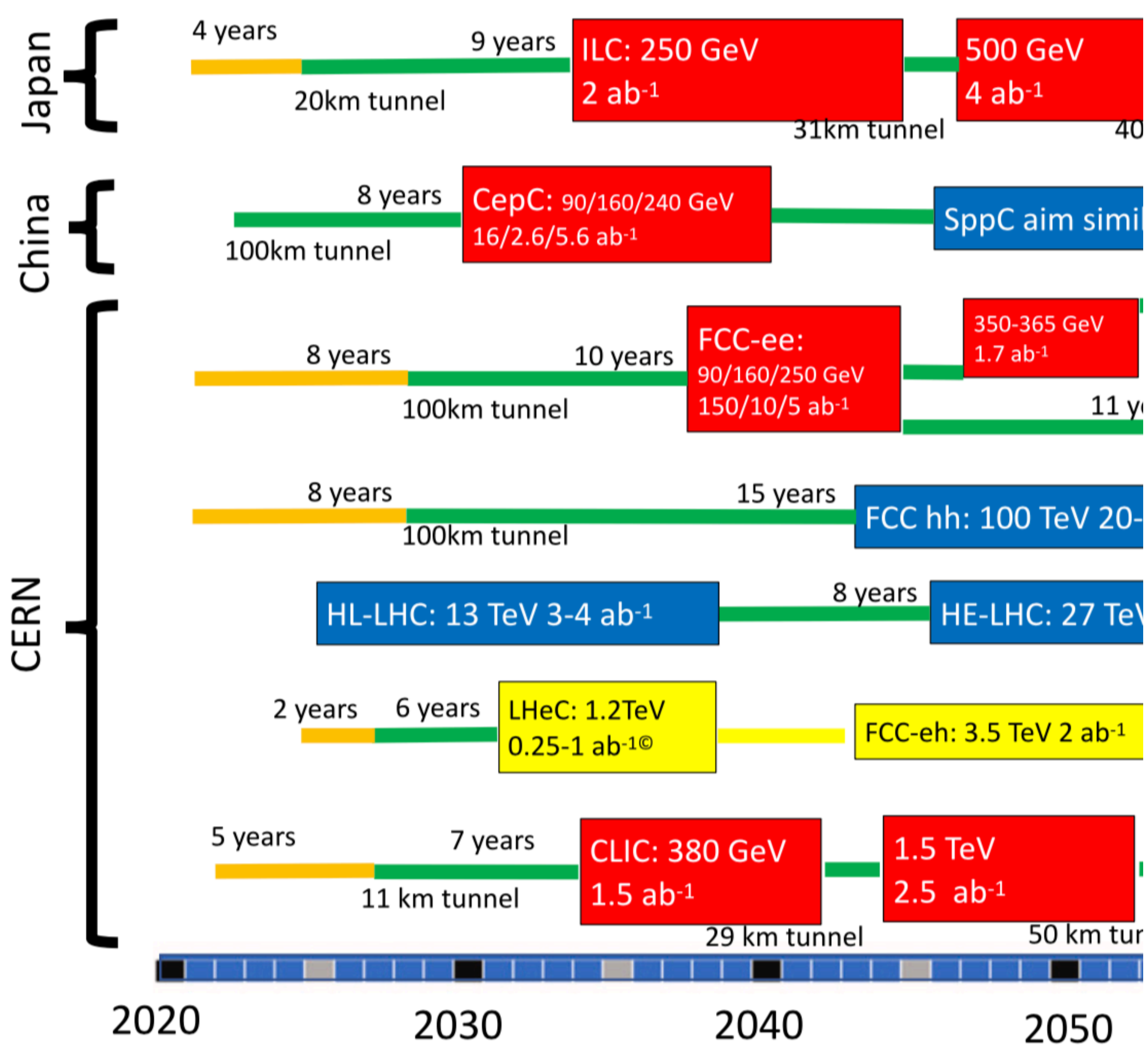
[arXiv:2102.05044, arXiv: 1904.03196, PRD 103, 076020, PRD 106, 056002,…]

-Now-: precision measurement



-Now-: precision measurement

Possible scenarios of future colliders



[Jorge de Blas, et al, arXiv:1907.04311]

μ (%)	Future Circular Colliders		
	CEPC	FCC-ee	
	240 GeV	240 GeV	365 GeV
	unpolarized		
σ_{Zh}	0.005	0.005	0.009
μ_{Zh}^{bb}	[illegible]	[illegible]	0.50
μ_{Zh}^{cc}	[illegible]	[illegible]	[illegible].50
$\mu_{Zh}^{\tau\tau}$	[illegible]	[illegible]	[illegible].80
$\mu_{Zh}^{\mu\mu}$	17.1	19.0	40.0
μ_{Zh}^{WW}	$0.98^{\dagger}$	1.20	2.60
μ_{Zh}^{ZZ}	$5.09^{\dagger}$	4.40	12.0
$\mu_{Zh}^{Z\gamma}$	15.0	15.9	–
$\mu_{Zh}^{\gamma\gamma}$	6.84	9.00	18.0
μ_{Zh}^{gg}	$1.27^{\dagger}$	1.90	3.50

New physics up to 100 TeV can be probed