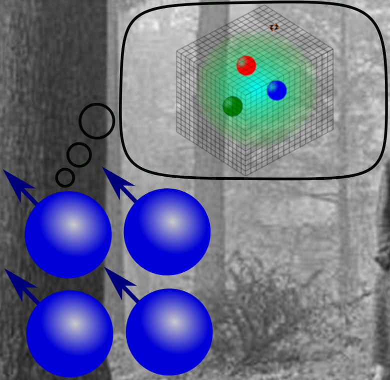
Quantum Simulations for High Energy Physics

Hank Lamm



My distillation of upcoming community white paper

Quantum Simulation for High-energy Physics

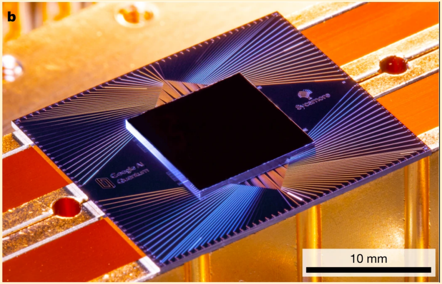
Christian Bauer,[1,a] Zohreh Davoudi,[2,b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7] Wibe A. de Jong,[1] Nate Gemelke,[8] Dmitri Kharzeev,[9] Henry Lamm,[5] Ying-Ying Li,[5] Yannick Meurice,[10] Benjamin Nachman,[1] Guido Pagano,[11] John Preskill,[12] Alessandro Roggero,[13,14] David I. Santiago,[15,16] Martin J. Savage,[17] Irfan Siddiqi,[15,16,18] George Siopsis,[19] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[20] and Other authors[21]

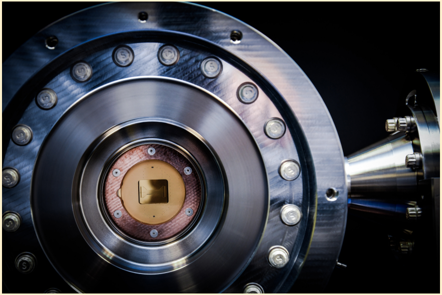
The real credit belongs to **Christian** and **Zohreh**

What is the state of QC? Nasty, brutish and short

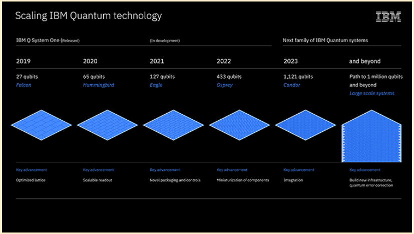
$\mathcal{O}(10^{1-2})$ qubits with entangling gate fidelities of $\sim 90 - 99\%$

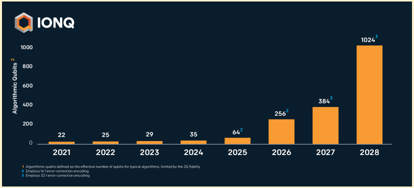
$\implies \mathcal{O}(10^{1-2})$ clock cycles with $\mathcal{O}(10^3)$ CLOPs

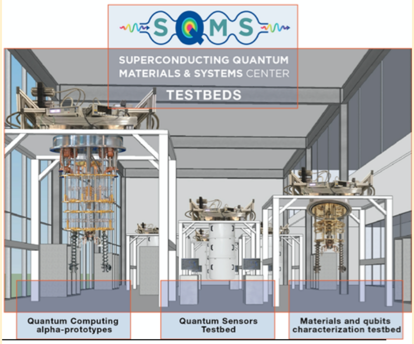




Where might we be by next Snowmass?







Roadmaps: $\mathcal{O}(10^3)$ qubits in **$\lesssim$10 years**

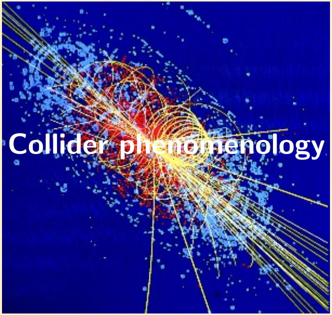
Varying levels of QEC & circuit depth

Similar to early LFT: $8^3 \times 20\ \mathbb{Z}_2$[1]

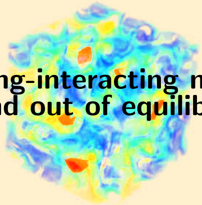
Important for theorists to be involved

[1] Creutz, M., L. Jacobs, and C. Rebbi. In: *Phys. Rev. D* 20 (1979). Ed. by Julve, J. and M. Ramón-Medrano.

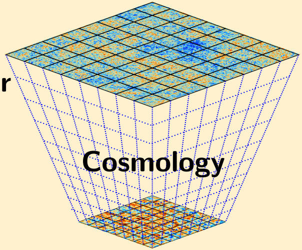
Fundamentally, HEP requires QC



Collider phenomenology

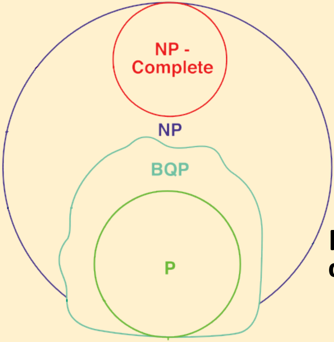


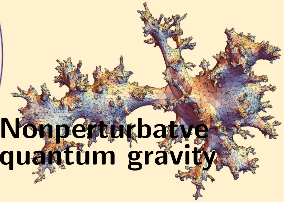
Strong-interacting matter in and out of equilibrium



Cosmology

Neutrino (astro)physics





Nonperturbatve quantum gravity

What could we learn?

Nonperturbatve & Nonequilibrium Physics

- What effect does quantum interference have on parton showers?[2]
- Does the QGP respect KSS conjecture?[3]
- How do quantum theories thermalize?[4]
- What is the neutron star equation of state observed with LIGO?[5]
- Are inflationary predictions robust to quantum preheating?[6]
- Do collective neutrino oscillations play a role in supernovae?[7]
- Does entanglement impose nontrivial constrains on bootstrap?[8]
- What are chiral fermions?
- What insight does quantum information give into quantum gravity?
- What is the behavior of nonperturbative SUSY?

[2] Bauer, C. W., M. Freytsis, and B. Nachman. In: (Feb. 2021). arXiv: 2102.05044 [hep-ph].

[3] Cohen, T. D., **H. Lamm**, S. Lawrence, and Y. Yamauchi. In: (Apr. 2021). arXiv: 2104.02024 [hep-lat].

[4] Jong, W. A. de et al. In: (June 2021). arXiv: 2106.08394 [quant-ph].

[5] Clemente, G. et al. In: *Phys. Rev. D* 101 (2020). arXiv: 2001.05328 [hep-lat].

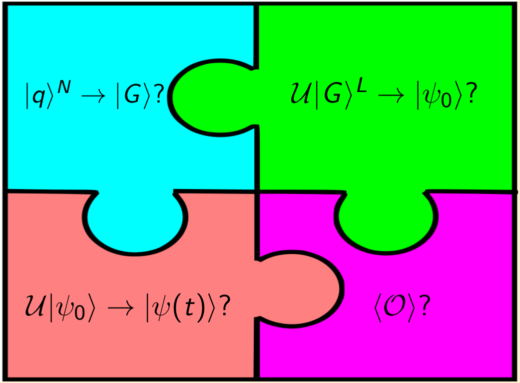
[6] Liu, J. and Y.-Z. Li. In: *Phys. Rev. D* 104 (2021). arXiv: 2009.10921 [quant-ph].

[7] Hall, B., A. Roggero, A. Baroni, and J. Carlson. In: *Phys. Rev. D* 104 (6 2021).

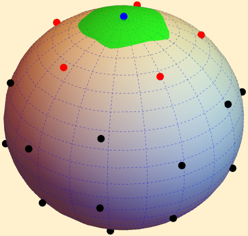
[8] Beane, S. R., D. B. Kaplan, N. Klco, and M. J. Savage. In: *Phys. Rev. Lett.* 122 (2019). arXiv: 1812.03138 [nucl-th].

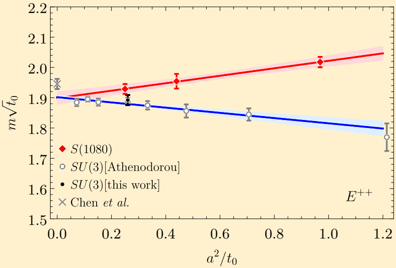
What "champagne problems" need to be solved?

- **Encoding**: How are bosons represented as registers?
- **Initalize**: How can registers be set to a state?
- **Propagate**: How can gates evolve states?
- **Evaluate**: How can observables be computed?



- **Mitigate**: Can LFT-specific QEC be cheaply designed?

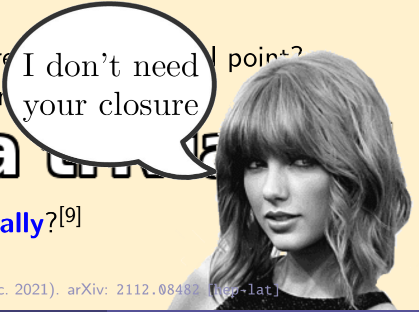




What qualities make a GOOD scheme?

- What **quantum resources** are require … point?
- What symmetries are being **broken** i…

This is not a



- Can the scheme be simulated **classically**?[9]

[9] Alexandru, A., P. F. Bedaque, R. Brett, and **H. Lamm**. In: (Dec. 2021). arXiv: 2112.08482 [hep-lat]

Today's η estimate: $\mathcal{O}(10^5)$ q & $\mathcal{O}(10^{49})$ T-gates[10]

- Quarks and Gluons on $L^d = 10^3$ lattice
- Use **Kogut-Susskind** Hamiltonian with $\mathcal{O}(a, a^2)$ errors
- Truncate to $\Lambda = 10$ in the electric field values
- Trotterization $\mathcal{U}(T)$ with **loose** error bound $\epsilon_{Trotter}$
- **Decomposing** unitary operators into native gates introduces $\epsilon_{synthesis}$
- $\epsilon \equiv \epsilon_{Trotter} + \epsilon_{synthesis} = 10^{-8}$

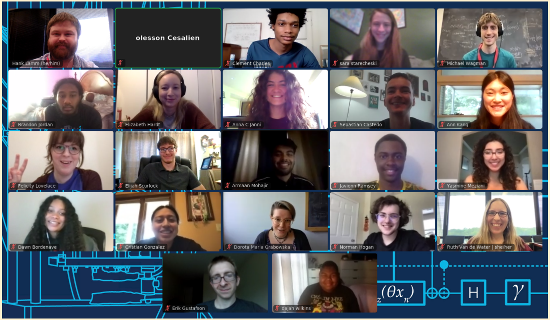
$$O\left(\frac{T^{3/2} d\Lambda L^{d/2}}{\epsilon^{1/2}}\left[d^2 L^d \mathcal{K}^2 \log(\mathcal{K}) + \log(\Lambda)\log(dL^d)\mathcal{C}\right]\right) \tag{1}$$

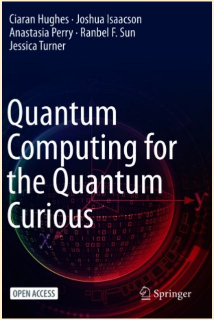
"Our analysis shows 99.998% of the gate counts stem from QFOPs... The SU(3) *heavy-ion collision* problem is then expected to require 9.04×10^{25} QFOPs. This equates to less than **three years** of runtime on an **exa-scale** quantum supercomputer."

[10] Kan, A. and Y. Nam. In: *arXiv preprint arXiv:2107.12769* (2021).

Developing quantum-ready theorists

- Quantum simulations of HEP require a **diverse and inclusive quantum-ready** workforce with skills **beyond** traditional HEP.
- Exciting research opportunities exist for as early as **high school**.
- Portfolio of funding mechanisms, career development opportunities, career paths and mentoring **will be required**.
- **QCIPU** exists today. Perhaps **QuTASI**? **Hackathons**?





It's time to go

Long-term impact likely larger for HEP than classical computing

- Devices are expected to rapidly scale
  - Theorists should be engaged **early**
  - **Toy models** simulations in $\lesssim$5 years
- Investigate desirable properties
  - **Entanglement in QG? Viscosity?, Cosmology?**
- Must improve over **expensive** algorithms
  - e.g. Consider theory errors, tighter bound on trotterization, reduce QFOPs
- Need to develop workforce with **new skills**