Quantum Application Survey:

Progress in Analog Quantum Computing

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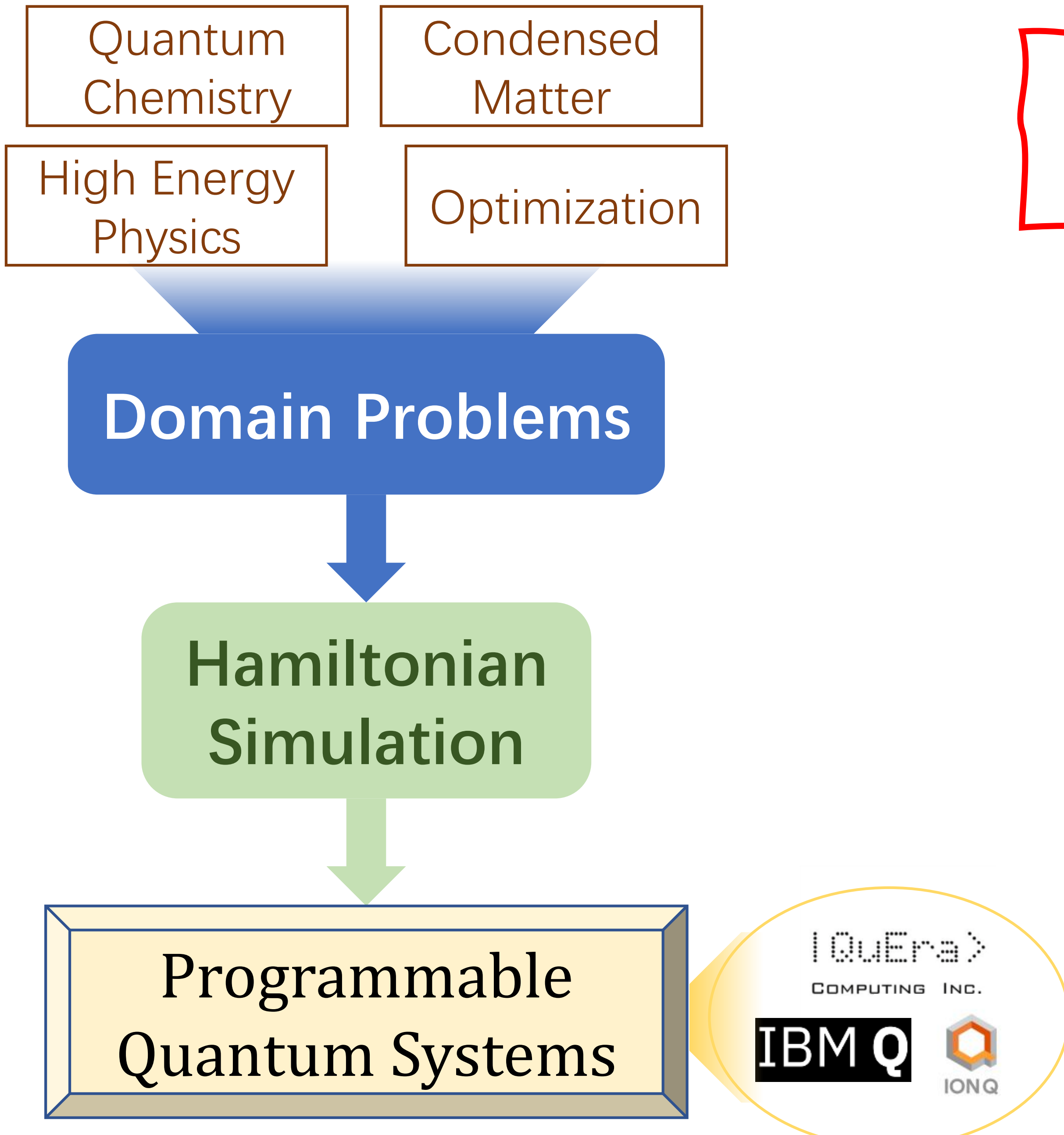
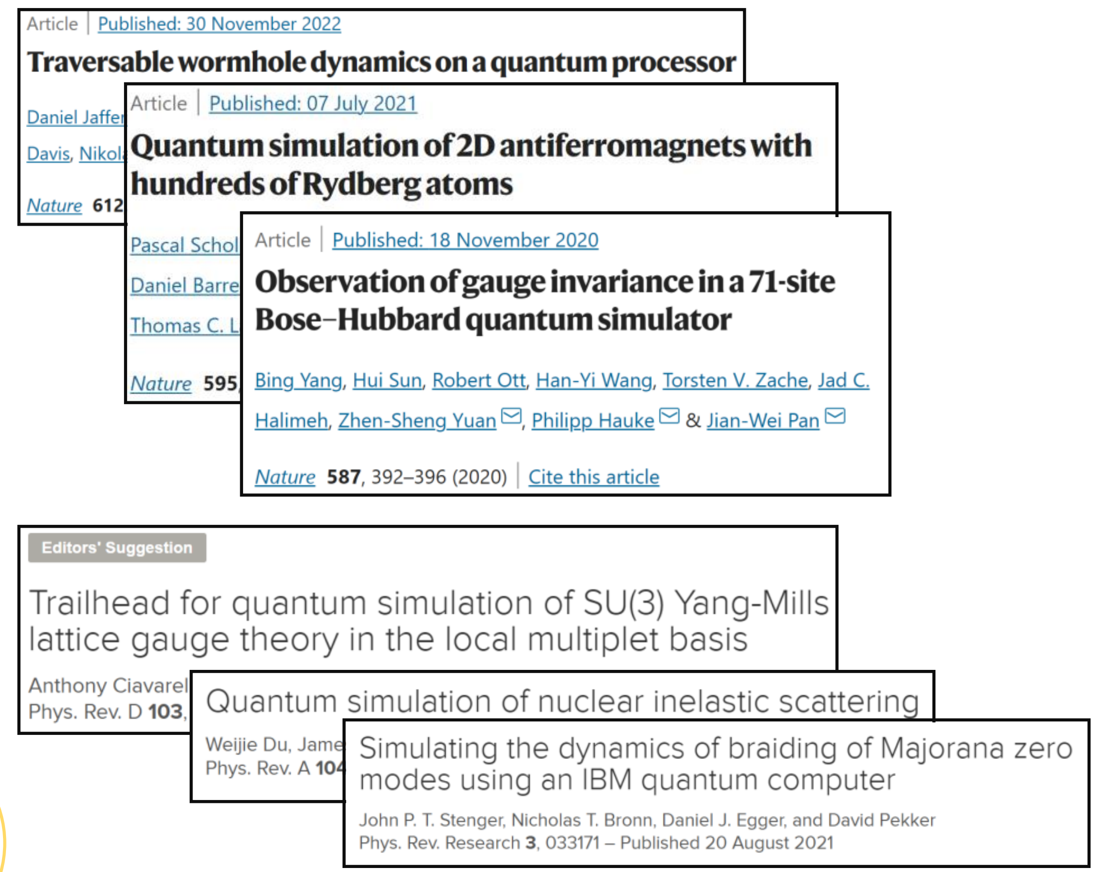
Physics-simulation-based Quantum Applications



>20 papers published since 2020 in Physics Review & Nature series


Article | Published: 30 November 2022
Traversable wormhole dynamics on a quantum processor
Daniel Jaffe... Davis, Nikol...
Nature 612...

Article | Published: 07 July 2021
Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms
Pascal Schol... Daniel Barre... Thomas C. L...
Nature 595...

Article | Published: 18 November 2020
Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator
Bing Yang, Hui Sun, Robert Ott, Han-Yi Wang, Torsten V. Zache, Jad C. Halimeh, Zhen-Sheng Yuan, Philipp Hauke & Jian-Wei Pan
Nature **587**, 392–396 (2020) | Cite this article

Editors' Suggestion
Trailhead for quantum simulation of SU(3) Yang-Mills lattice gauge theory in the local multiplet basis
Anthony Ciavarel...
Phys. Rev. D **103**, ...

Quantum simulation of nuclear inelastic scattering
Weijie Du, Jame...
Phys. Rev. A **104**...

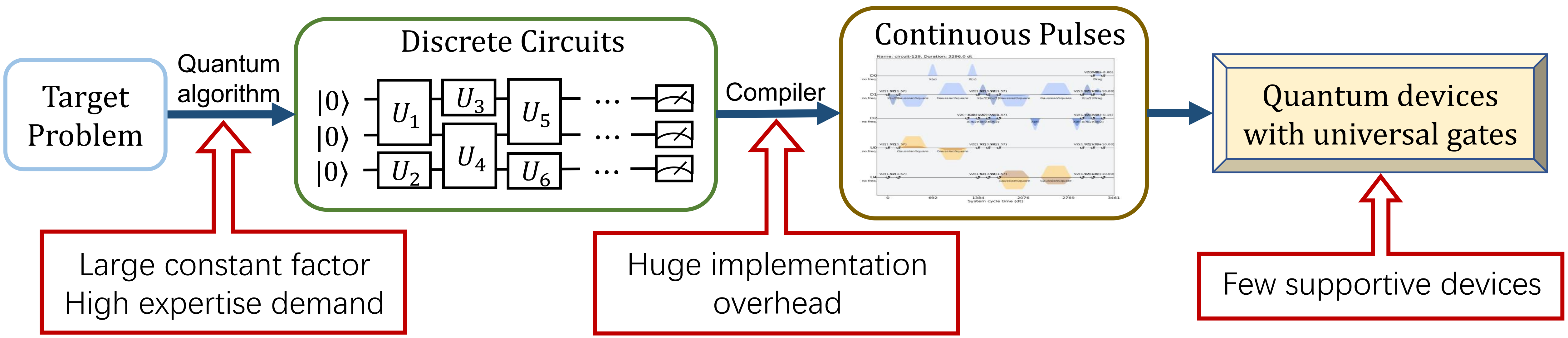
Simulating the dynamics of braiding of Majorana zero modes using an IBM quantum computer
John P. T. Stenger, Nicholas T. Bronn, Daniel J. Egger, and David Pekker
Phys. Rev. Research **3**, 033171 – Published 20 August 2021

• • •

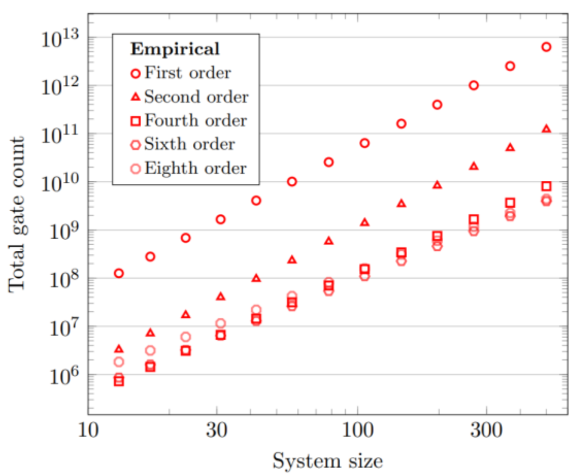
- A major application of quantum computing with early feasibility
- Amenable to both circuit-model and Hamiltonian-model implementation
- Recent pulse-level control of quantum devices enables investigation of both

Circuit-based Digital Implementation is Expensive

Digital Quantum Computing Paradigm



[1]:



On IBM devices:
$10 \cdot T_{\text{CNOT}} \approx T_1 \approx T_2$
$T_{R_{XX}(\theta)} \approx 2 \cdot T_{\text{CNOT}}$

Available:
Superconducting
Ion Trap

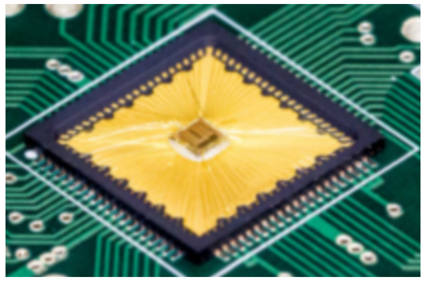
[1]: Childs et al., Toward the first quantum simulation with quantum speedup, PNAS, 2018.

- Circuit-model is a well-recognized theoretical model/interface between quantum applications and hardware, w/ merits in its mathematical elegance.
- Overheads w/ circuit abstraction. Resource-Efficient Quantum Computing by Breaking Abstractions [IEEE]
- Mismatch in quantum & classical hardware specs: clock rate, hardware acceleration
- Asymptotic theoretical speedup (circuit) $\neq >$ speedup in practice [CACM, May 2023; q. IPM]

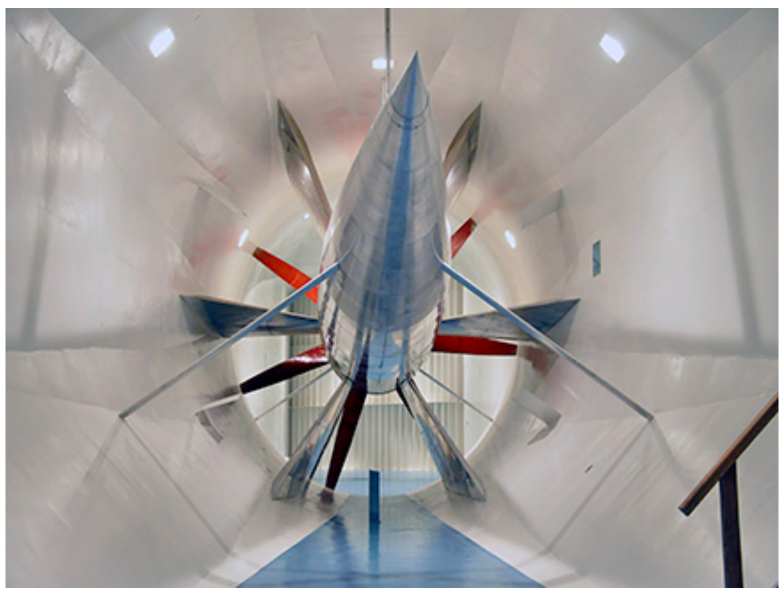
Hamiltonian-based Analog Machines

Analog computing predates digital computing, and revives recently due to challenges in scaling up digital computing (e.g. Moore's law).

- *Energy Efficiency — low overhead*
- *Domain applications like analog AI chip*

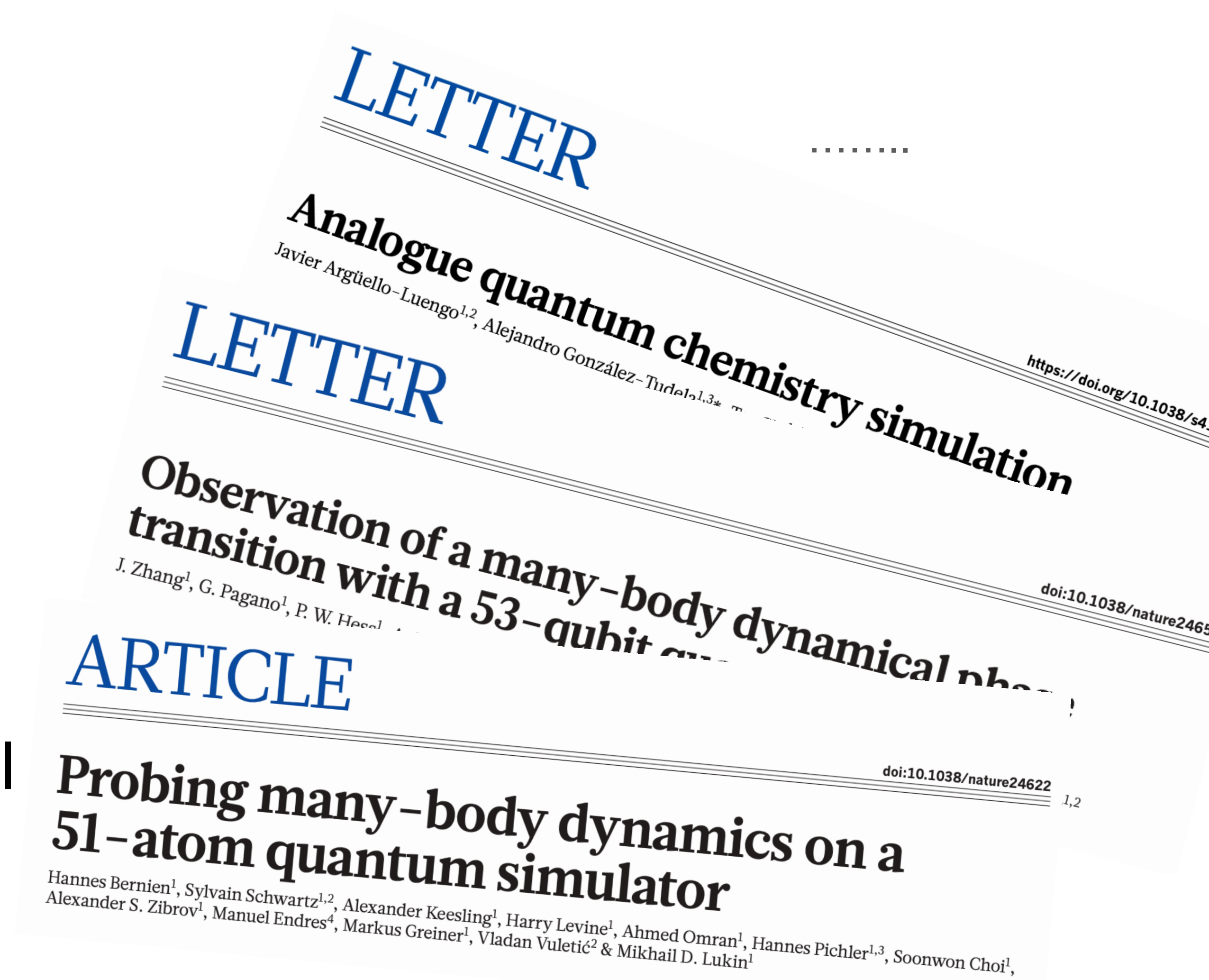


HCDCv2 Analog Devices
(Columbia University)



Wind Tunnels & Various Testbeds remain the standard solutions in practice for many domain applications.

Analog Quantum Simulators are not unfamiliar either.



LETTER

Analogue quantum chemistry simulation

Javier Argüello-Luengo[1,2], Alejandro González-Tudela[1,3]

https://doi.org/10.1038/s4

LETTER

Observation of a many-body dynamical pha
transition with a 53-qubit

J. Zhang[1], G. Pagano[1], P. W. Hess

doi:10.1038/nature2465

ARTICLE

doi:10.1038/nature24622

Probing many-body dynamics on a 51-atom quantum simulator

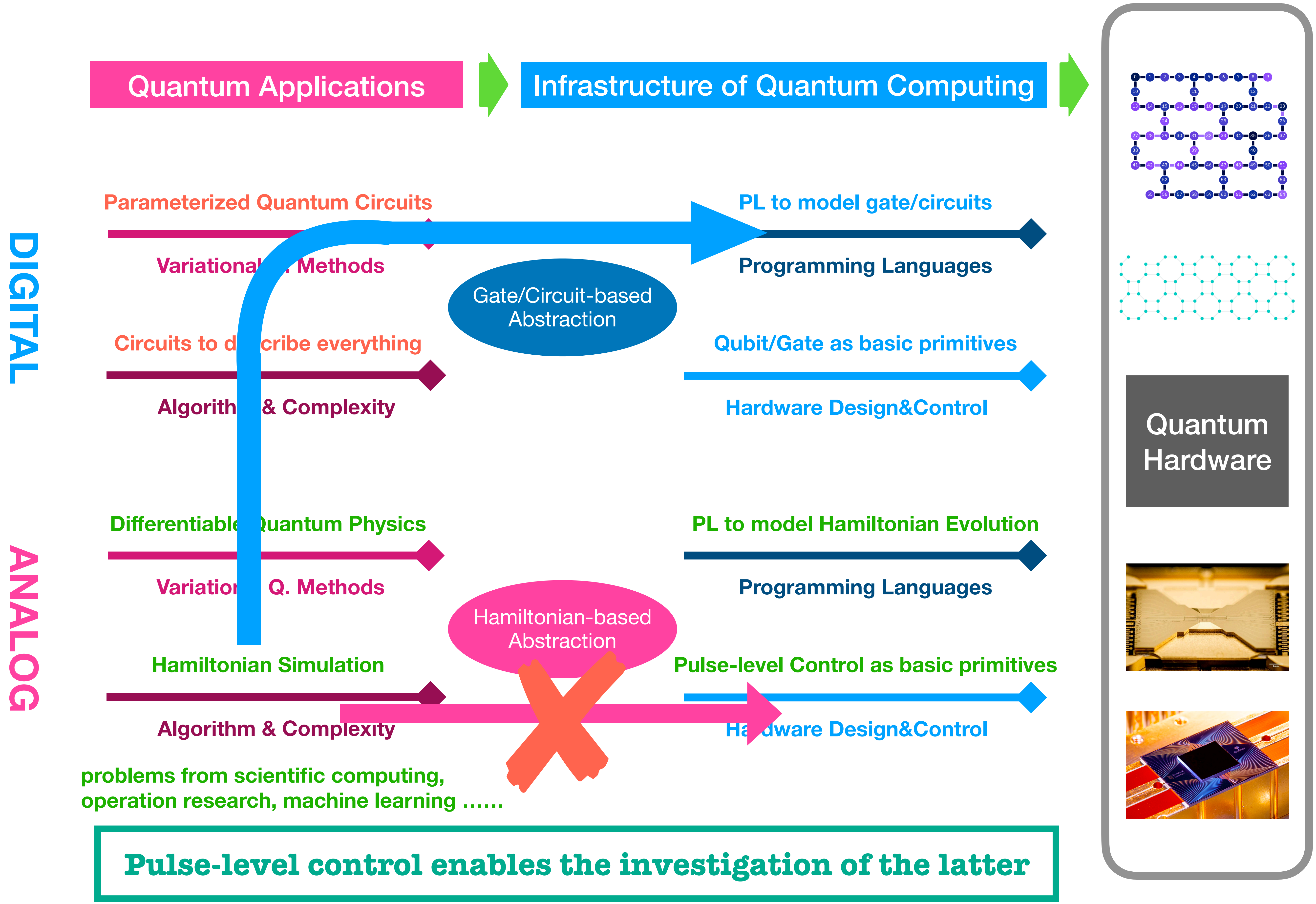
Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

....

The Analog Milestone for QC:
Understand unknown physics w/ help of analog/special-purpose quantum machines!

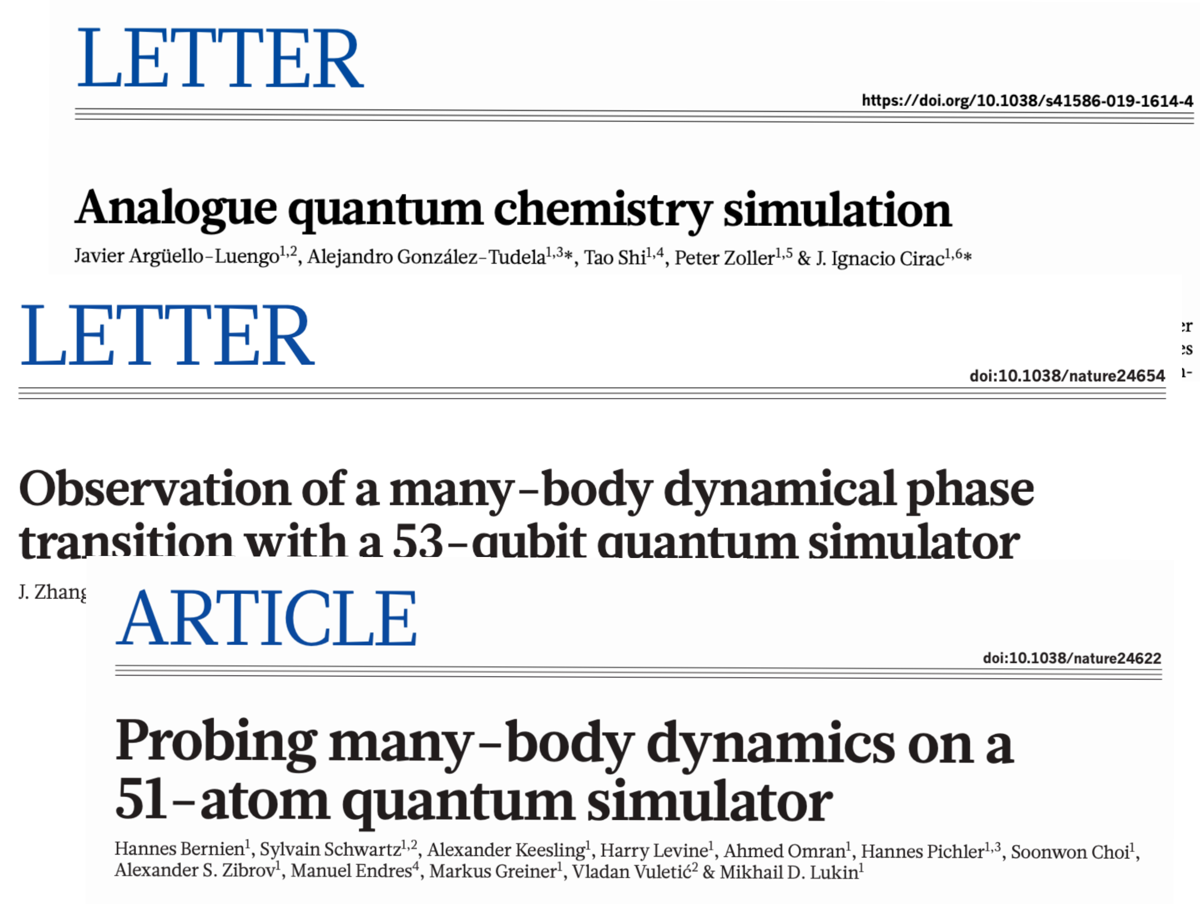
We believe **analog thinking** & **tool-chain** will be critical to achieve this milestone!

Conceptual Differences between circuit and Hamiltonian models



Examples of Hamiltonian-based Demonstration

- Physical phenomena: quantum scar, phase transition, spin liquid, or so
- Neutral atoms (QuERA, Pasqal), Trapped Ions, Superconducting (IBM, Rigetti)
- Leverage native programmability of quantum devices, but w/ more complicated error models, lacks a fault-tolerant theory and a nontrivial use of native Hamiltonian (for now)


LETTER

https://doi.org/10.1038/s41586-019-1614-4

Analogue quantum chemistry simulation

Javier Argüello-Luengo[1,2], Alejandro González-Tudela[1,3]*, Tao Shi[1,4], Peter Zoller[1,5] & J. Ignacio Cirac[1,6]*

LETTER

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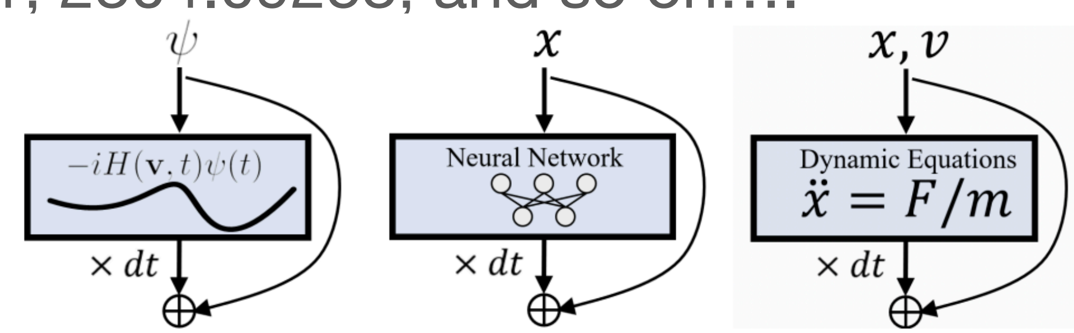
Simulation -> Differentiable Simulation / variational methods

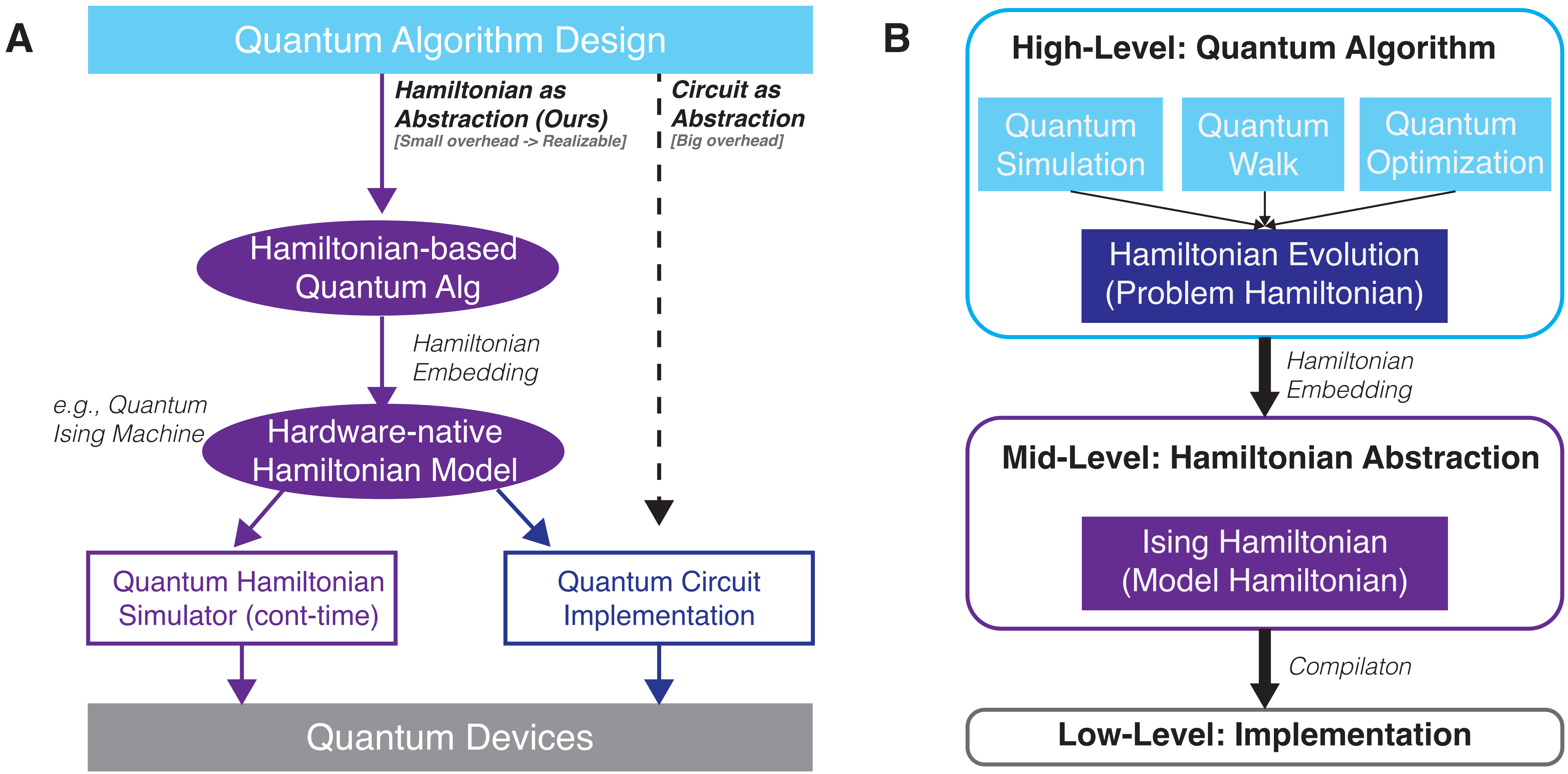
- Leveraging pulse-ansatz for variational methods: 2008.04302, 2202.08908, 2208.01215, 2211.02584, 2211.02748, 2212.12911, 2304.09253, and so on….



(a) Diff. Analog QC (b) Neural ODE (c) Diff. Physics

- We developed an auto-differentiation training method for differentiable quantum physics (NeurIPS 2022), demonstrate orders of magnitude advantage on simulators.

Hamiltonian-oriented Algorithm Design: beyond naive cases



- Hamiltonian-oriented design: both (1) **new quantum algorithms** and (2) **more efficient implementation** of existing quantum algorithms
- Apply to both *near-term* and *long-term* quantum devices
- Key new technique in implementation is the **Hamiltonian embedding** scheme

Hamiltonian-oriented Algorithm Design: Examples

	Continuous Optimization	Quantum PDE Solvers	Particle in real space & Dirac equation	Quantum Walk & Spatial Search
New Quantum Algorithm	**Q**uantum **H**amiltonian **D**escent derived from the *path integral* of continuous-time classical gradient flow Superior Performance in TTS (Time-To-Solution) than *quantum adiabatic* and *five classical SOTA algs* on **75-dim** quadratic programming instances	Quantum PDE Solver for First-order hyperbolic equations (e.g, Hamilton-Jacobi, Heat, Liouville's) Via embedding classical dynamics into Schrödinger equation	No new quantum algorithm	
New Implementation: Hamiltonian Embedding	Hamming Encoding Quantum Ising Machine	Unary encoding + Anti-Ferromagnetic (AF) Quantum Ising Machine	Anti-Ferromagnetic (AF) + One-shot Encoding Quantum Ising Machine	
Platforms	Using D-Wave as an analog quantum simulator	Neutral Atoms	Neutral Atoms/Trapped Ions	

Hamiltonian-oriented Algorithm Design: Examples

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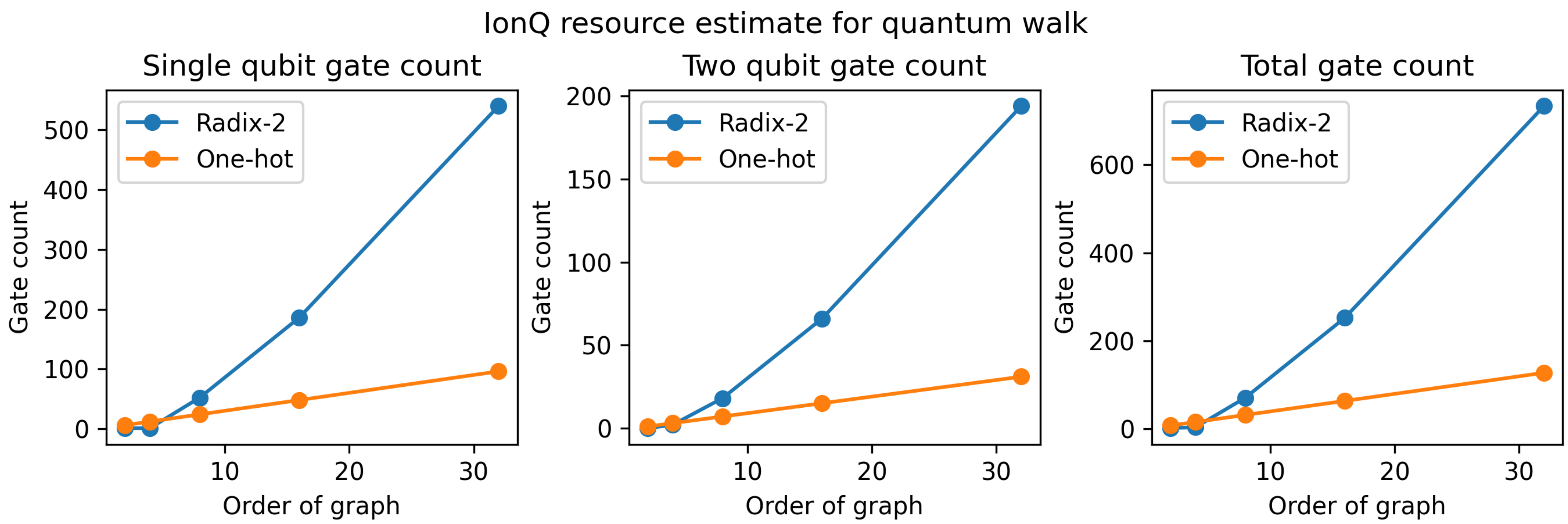
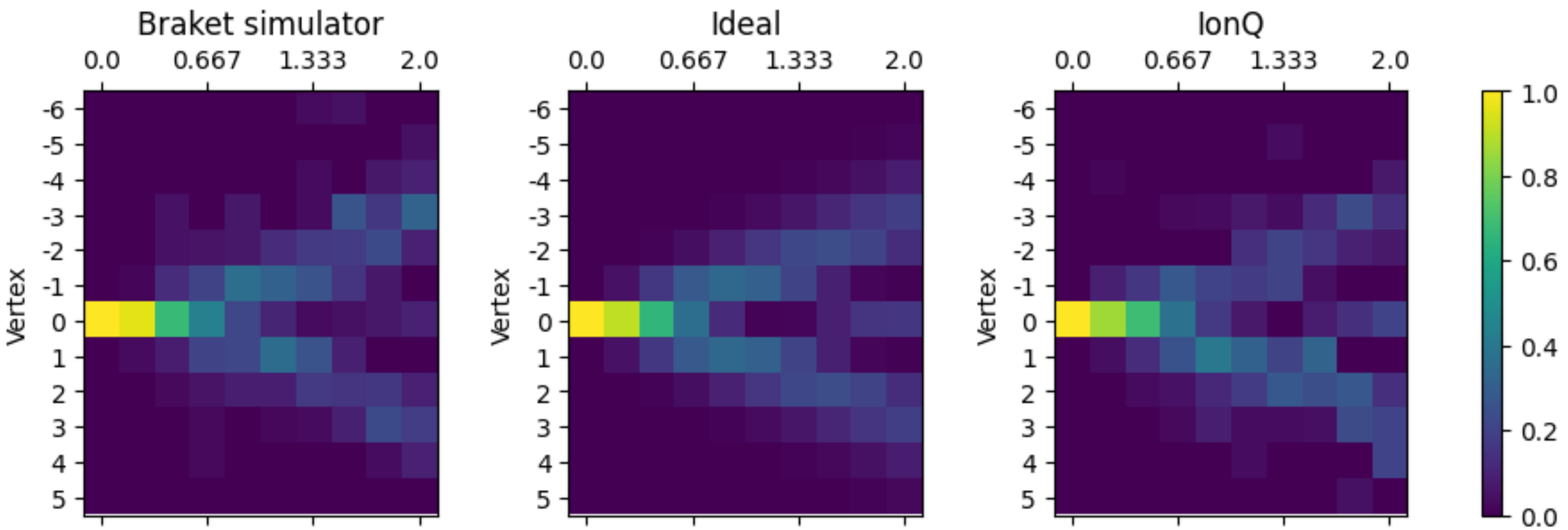
New Implementation: Hamiltonian Embedding	Hamming Encoding Quantum Ising Machine	Unary encoding + Anti-Ferromagnetic (AF) Quantum Ising Machine	Anti-Ferromagnetic (AF) + One-shot Encoding Quantum Ising Machine	
Platforms	U … n anal … ator	Neutral Atoms	Neutral Atoms/Trapped Ions	

QHD Website

1-D quantum walk example: early view on IonQ Aria





Example:

12-vertices 1-D quantum walk

Via one-shot encoding

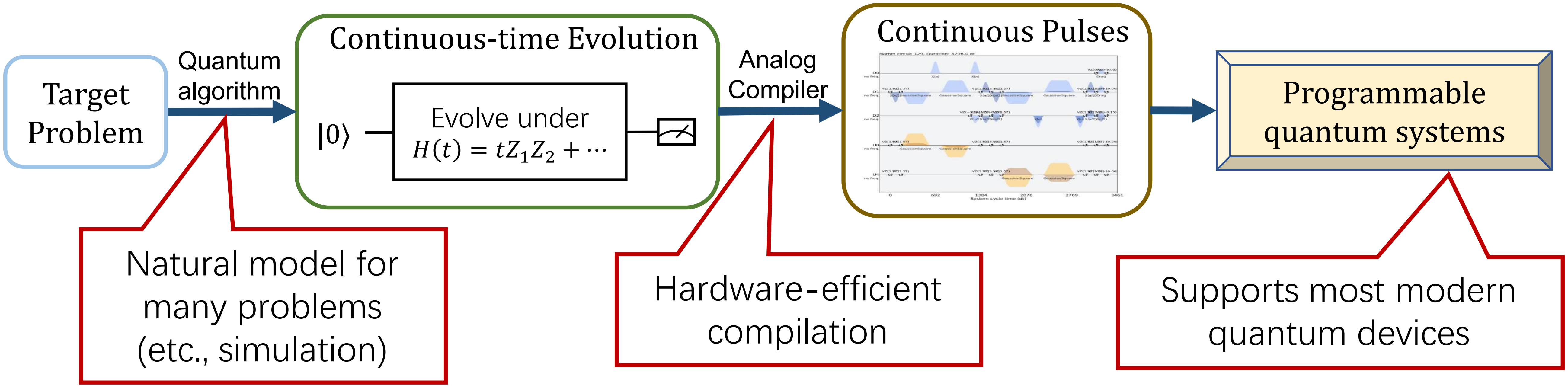
Accessed on 05-17-23

33 USD on Braket

Infrastructure for Hamiltonian-oriented Programming

Ready for modern quantum devices!

Analog (Hamiltonian-oriented) Quantum Computing Paradigm



ABSTRACTION & SOFTWARE?

SIMUQ

SIMUlation language for **Q**uantum

Enhance your capability of harnessing the power of quantum devices

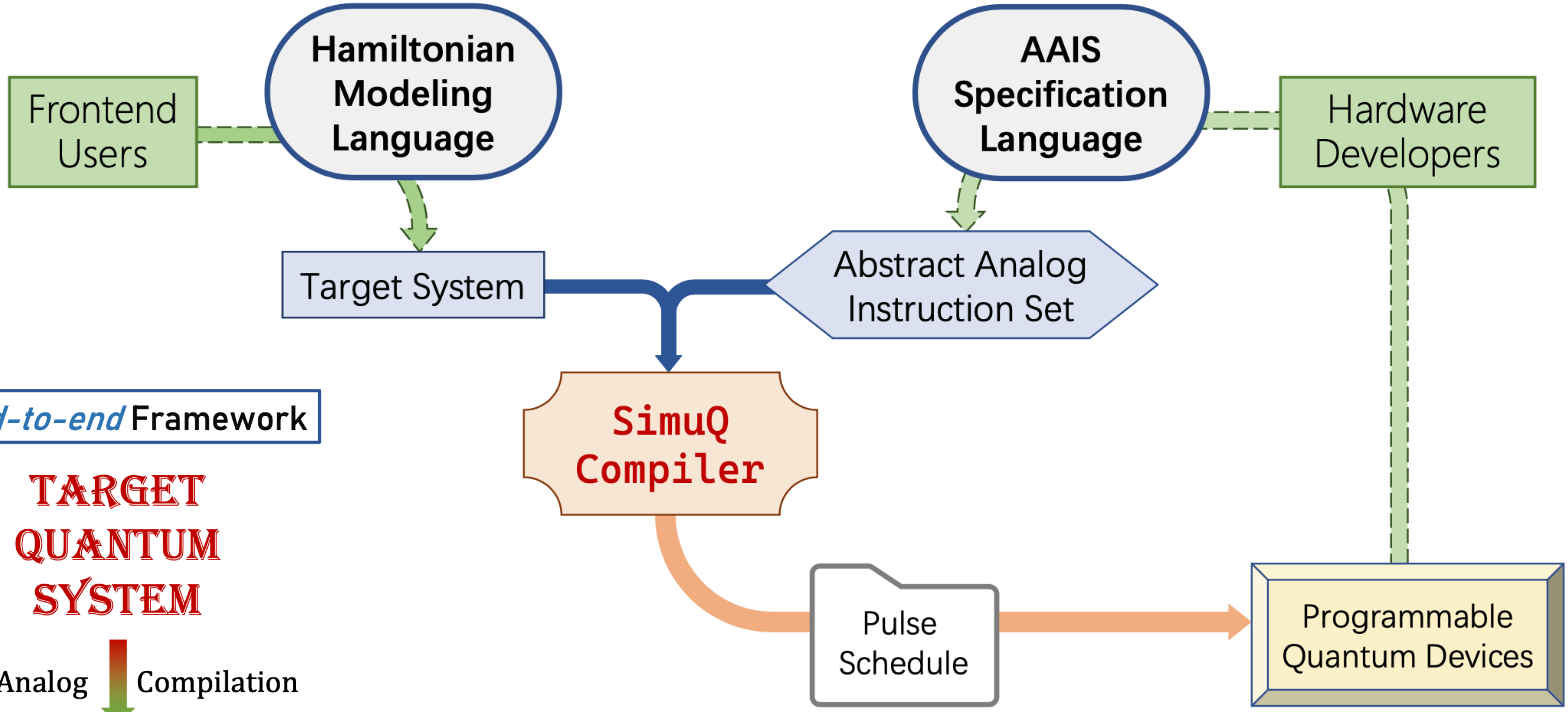
GitHub repo:
https://github.com/PicksPeng/SimuQ

arXiv: 2303.02775

Project website:
https://pickspeng.github.io/SimuQ/

SimuQ Framework

All our Hamiltonian-oriented applications are now coded w/ SimuQ !!!



End-to-end **Framework**

TARGET QUANTUM SYSTEM

Analog ↓ Compilation

EXECUTABLE PULSES

Currently support IBM (via Open-Pulse), Rigetti (Braket Pulse), QuERA as well as arbitrary-angle MS gates on Trapped Ions

Enhance your capability of harnessing the power of quantum devices

GitHub repo:
https://github.com/PicksPeng/SimuQ

arXiv: 2303.02775

Project website:
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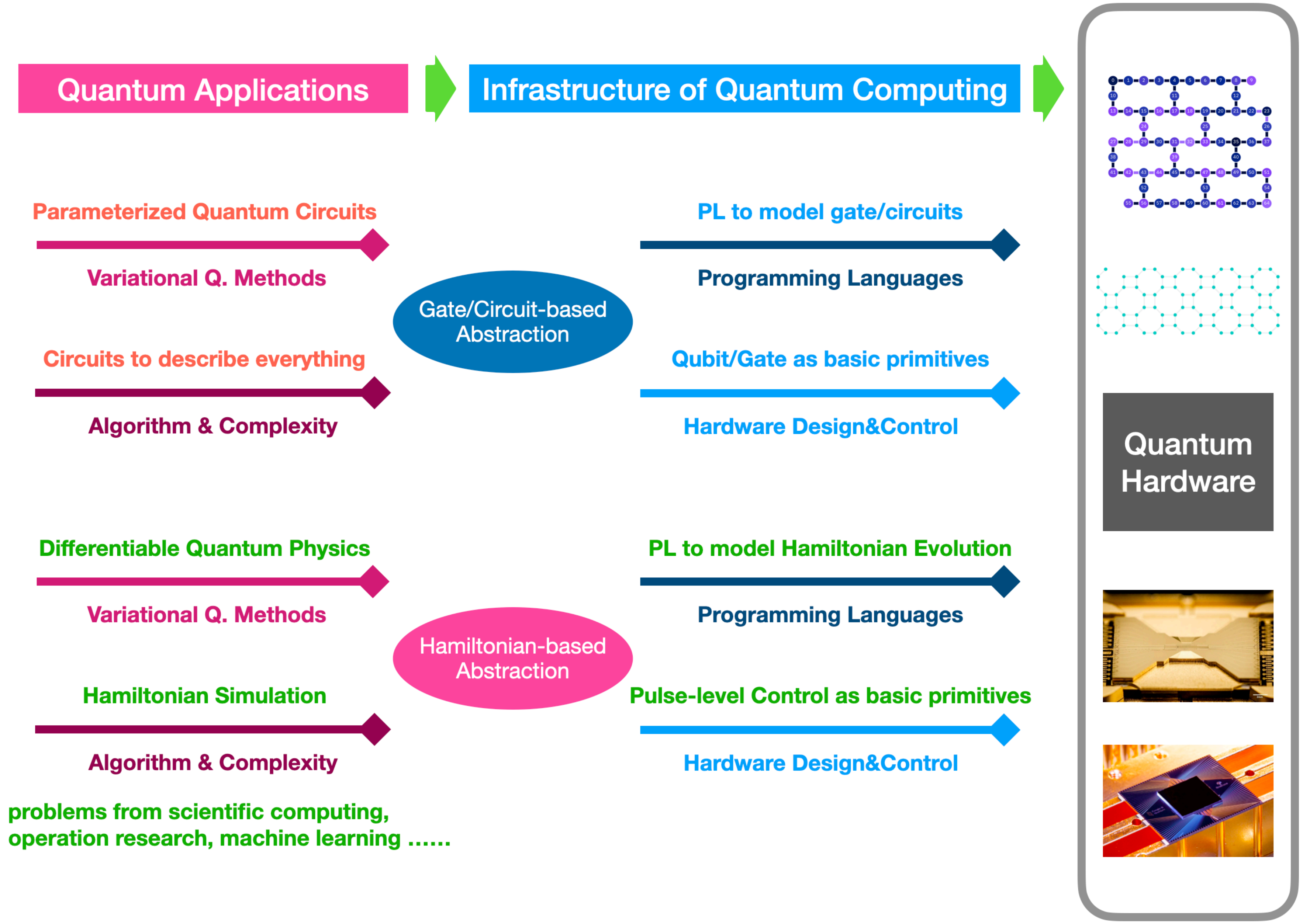

Postdocs

Liyi Li (2020-2023. Asst. Prof. at Iowa)
Xiong Fan
(2020-2021. Assistant Prof. at Rutgers)
Robert Rand
(2018-2020. Assistant Prof. at U Chicago)

Thank You!